SUPRASPINATUS: AN IN-VIVO INVESTIGATION OF MUSCLE ARCHITECTURE IN RESPONSE TO SURGERY AND EXERCISE

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Abstract

Rotator cuff pathologies involving supraspinatus are a common cause of musculoskeletal morbidity and can lead to significant disability affecting the overall quality of life. Architectural parameters of the muscle directly influence its functional properties. Therefore, understanding of fiber bundle changes with surgery and different exercises can assist clinicians in planning better surgical and shoulder rehabilitative protocols. The first objective of this thesis was to systematically review human cadaveric studies of the normal supraspinatus architecture and highlight the key aspects that should be considered while performing studies of skeletal muscle architecture. The second objective was to understand the impact of surgical repair on the structural and functional recovery of the supraspinatus. The final objective was to provide a scientific rationale behind choosing an exercise to strengthen supraspinatus by investigating its muscle architecture. **Study 1** systematically reviewed human cadaveric studies of the normal supraspinatus architecture. Results showed that the overall quality of majority of included is poor and there was a large range in the reported architectural values of the entire muscle. In conclusion, there were only a few studies providing the level of detail and quality suitable for advancing our understanding of shoulder biomechanics. **Study 2** quantified and compared the fiber bundle architecture of the pathologic supraspinatus pre- and post-operatively at multiple time points. Results showed significant lengthening of fiber bundles after one month of surgery which then decreased significantly by 6 months of surgery. In contrast, an initial decrease followed by an increase in pennation angle overtime was found. The results suggest that the stretching applied to the tendon and muscle during repair could affect the length-tension relationship of the muscle, which in turn can compromise its function and may lead to inferior surgical outcomes. **Study 3** compared the efficacy of three commonly prescribed supraspinatus strengthening exercises in the rehabilitation setting based on the architectural changes following resistance training. Results showed there was no change in FBL and increased strength after resistance training with prone horizontal abduction exercise. Findings suggest that prone horizontal abduction may be a more suitable exercise to strengthen supraspinatus.

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Rohit Sachdeva

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List of Abbreviations

10 RM	Ten repetition maximum
AB	Angela Busch
ANOVA	Analysis of variance
ap	Anterior posterior
CSA	Cross sectional area
CT	Computed tomography
EC	Empty-can group
ELH	Elizabeth Louise Harrison
EPICOT	Evidence, population, intervention, comparator, outcomes and timestamp
ER	External rotation
FBL	Fiber bundle length
FC	Full-can group
GS	Gyung Won Son
HHD	Hand-held dynamometer
ISP	Infraspinatus
JB	Julia Bidonde
kg	Kilograms
ml	Medial lateral
ML	Muscle length
MRI	Magnetic resonance imaging
MV	Muscle volume
PA	Pennation angle
PCSA	Physiological cross sectional area
PHA	Prone horizontal abduction group
PRISMA	Preferred reporting items for systematic review and meta-analysis
RS	Rohit Sachdeva
SD	Standard deviation
SF	Supraspinous fossa
SK	Soo Kim
sk	Skin

SP	Supraspinatus
SSC	Subscapularis
SYK	Soo Young Kim
TP	Trapezius
US	Ultrasound
WHQ	Waterloo handedness questionnaire
WORC	Western Ontario Rotator Cuff

Units

cm	Centimeters
cm^2	Square centimeters
cm^3	Cubic centimeters
°	Degrees
mm	Millimeters
Ө	Angle

Preface

This thesis is arranged in five chapters. The first chapter is the main introduction to the dissertation and outlines the theme and specific objectives. Chapters Two, Three and Four focus on the objectives outlined in Chapter One and are written so that each chapter can be considered as an independent stand-alone manuscript.

The first manuscript (Chapter Two), a systematic review, descriptively analyses the previous cadaveric studies on the normal supraspinatus architecture. The main aim of the manuscript was to systematically identify published studies on the architecture of normal supraspinatus through a comprehensive literature search and describe and synthesize their methods, results and conclusions. The methodological quality of the selected studies was also assessed based on a checklist specifically designed by the reviewers. This manuscript is the result of a team consisting of five reviewers (RS, AB, LH, JB, SK), one librarian and one summer research student (GS) who were engaged in planning of the systematic review, outlining search criteria, screening and extracting the data, developing a quality assessment tool, reviewing and approving the final draft of the manuscript. Although this manuscript was prepared with a collaborative approach of a team, the most substantial contribution was made by the graduate student researcher (RS).

The second manuscript (Chapter Three) examines the *in-vivo* architecture of the pathologic supraspinatus after surgical repair. The main goal of this manuscript was to understand the impact of surgical repair on muscle architecture by investigating and comparing the changes in the FBL, PA & MT of supraspinatus pre- and post-operatively at multiple time points.

The third manuscript (Chapter Four) investigates the efficacy of three common supraspinatus strengthening exercises based on the architectural changes and abduction strength following resistance training. The aim of the study was to add to the scientific basis of commonly performed rehabilitation exercises to develop safe and effective exercise programs for rehabilitation and injury prevention.

Finally, Chapter Five presents a summary of findings and the directions for future research.

CHAPTER ONE

INTRODUCTION

1.1 Rotator Cuff Pathology

Rotator cuff pathologies are a common cause of musculoskeletal morbidity and can lead to significant disability affecting activities of daily living and reductions in the overall quality of life (Yamamoto et al., 2010). In United States, more than 75,000 rotator cuff repairs are performed annually, and an estimated total average cost of rotator cuff repair was reported to be $10,605 (Vitale et al., 2007). This represents a substantial economic burden for the public and private healthcare systems. Moreover, the frequency of occurrence of rotator cuff pathologies in the working population is high, affecting productivity at the workplace as a result of absenteeism posing a significant economic burden for employers (Herberts et al., 1984; Yamaguchi et al., 2001).

Among rotator cuff pathologies, tears of the rotator cuff tendon are very common which can be categorized into partial and full-thickness tears. These tears are often accompanied by shoulder pain, a decrease in strength and limited range of motion (Reilly et al., 2006). However, reports have shown that individuals may have asymptomatic rotator cuff tears which with time may become symptomatic and progress in size (Yamaguchi et al., 2001). Yamanaka & Matsurnoto (1994) followed 40 partial-thickness tears over two years and reported enlargement of the tear in 52.5% (21/40) and progression to full-thickness tears in 27.5% (11/40) of cases. Furthermore, full-thickness tears do not heal spontaneously (Yamaguchi et al., 2001).

1.2 Prevalence of rotator cuff tears

The prevalence of symptomatic or asymptomatic partial and full-thickness rotator cuff tears varies in the literature and has been reported to be up to 80% in the elderly population (Milgrom et al., 1995). Magnetic resonance image (MRI) scanning of 96 subjects demonstrated partial or full-thickness tears in 54% (25) of subjects over the age of 60 years and in 4% (1) of subjects aged less than 40 years (Sher et al., 1995). Similarly, an increased incidence of rotator cuff tears with age was found in other studies (Minagawa et al., 2013; Yamamoto et al., 2010). In a retrospective study, Reilley et al. (2006) reported the prevalence of full-thickness and partial-thickness tears to be 11.75% and 18.49% respectively in a total of 2553 cadaveric shoulders.

The prevalence of rotator cuff tears in the general population has also been reported. Minagawa et al. (2013) performed ultrasonography of bilateral shoulders in 664 subjects and reported an incidence of full-thickness tears in 22.1% of subjects (147) with symptomatic tears accounting for 34.7% (51 of 147) and asymptomatic 65.3% (96 of 147). Yamamoto et al. (2010)

had similar results and reported the prevalence of rotator cuff tears in the general population to be 20.7% (283/1366 shoulders) regardless of the presence or absence of symptoms.

1.3 Aetiology of rotator cuff tears

Rotator cuff tears can be traumatic or non-traumatic. In the literature, the mechanisms of rotator cuff tears have been explained by intrinsic and extrinsic factors or combination of both. Intrinsic factors include the degeneration of the rotator cuff tendons due to the natural process of aging (Codman & Akerson, 1931,Tempelhof et al.,1999) and decreased vascularity (Fukuda et al., 1990). In an ultrasound (US) study, Tempelhof et al. (1999) examined 411 subjects and found a positive correlation between age and cuff tears.

Extrinsic factors include compression of the rotator cuff tendons and associated tissues within the subacromial space (Neer, 1983). Many studies have suggested variations in acromial shape as the cause of impingement lesions (MacGillivray et al., 1998; Wang et al., 2000). In a cadaveric study, Bigliani et al. (1986) classified the morphology of acromion into three types: Type I (flat), Type II (curved) and Type III (hooked). They found full-thickness tears in 33% of the cases, of which, 73% of tears were associated with hooked acromion suggesting greater narrowing of the subacromial space and compression of rotator cuff tendons.

1.4 Supraspinatus

Typically, rotator cuff tears involve the supraspinatus tendon. In a prospective study of 191 patients with full-thickness tears, Smith et al. (2000) found tears of supraspinatus in 190 patients. Supraspinatus plays a major role in shoulder abduction and external rotation. Along with other rotator cuff muscles, supraspinatus also provides dynamic stability to the shoulder joint (Moore et al., 2002). Therefore, any injury to supraspinatus can severely affect the normal functioning of the shoulder joint. Furthermore, loss of supraspinatus function may impose excessive strain on the other rotator cuff tendons and increase the risk of injury (Perry et al., 2009).

Supraspinatus consists of architecturally distinct anterior and posterior regions (Kim et al., 2007; Kim et al., 2010; Roh et al., 2000). Based on the physiological cross sectional area (Roh et al., 2000) and muscle volume (Kim et al., 2007), the larger anterior region has been suggested to be responsible for most of the force production while the smaller posterior region is thought to maintain and quickly adjust tension on the tendon (Kim et al., 2013). Depending on the attachment sites and fiber bundle orientation, Kim et al., (2007) further sub-divided the anterior and posterior regions into superficial, middle and deep parts (Figure 1.1).

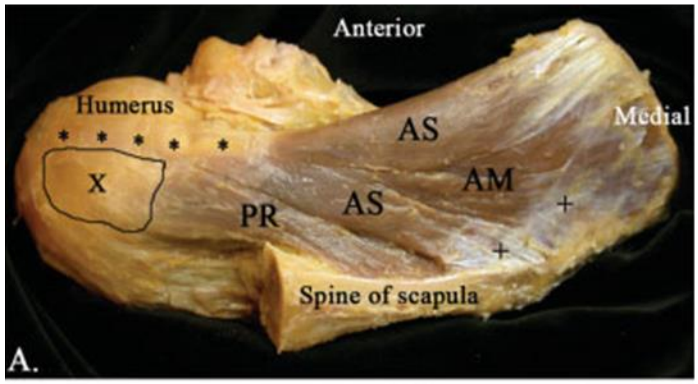

Figure 1.1 Dissection of the architecturally distinct regions of left shoulder supraspinatus. AS, superficial part of anterior region; AM, middle part of anterior region; PR, posterior region; **, anterior part of the supraspinatus tendon. Adapted from Kim et al., 2007.

1.5 Management and Surgical Failure

Treatment options for rotator cuff tears vary from conservative physiotherapy management to surgical interventions such as arthroscopic or open repair followed by 20-22 weeks of rehabilitation (Millett et al., 2006). Despite the extensive amount of research on the management of rotator cuff tears, there are several issues that remain controversial regarding the treatment of rotator cuff tears including the most appropriate surgical technique, optimal time for surgical repair, and the best exercise to strengthen the supraspinatus (WilliamsJr et al., 2004).

Exercise therapy is often offered as the first management approach for patients with full-thickness rotator cuff tears (Ainsworth & Lewis, 2007). Based on shoulder and scapular kinematics, electromyography (EMG) and MRI studies, several exercises have been proposed in the literature to strengthen the supraspinatus including full-can (Reinold et al., 2007; Thigpen et al., 2006), empty-can (Jobe & Moynes, 1982), prone horizontal abduction (Blackburn et al., 1990) and external rotation exercises (Boettcher et al., 2009). However, to date, there is a lack of consensus regarding the most suitable exercise to strengthen the supraspinatus.

Surgical repair of the rotator cuff tears is indicated when non-operative treatment fails. The techniques of repair varies from invasive procedures such as traditional open repair to more advanced non-invasive procedures such as arthroscopic surgery. In contrast to arthroscopic repair which has potential advantages of less pain, preservation of the deltoid muscle and attachment site and faster recovery (Nho et al., 2007), open repair has been associated with severe early post-operative pain and deltoid morbidity (Baker & Liu, 1995; Levy et al., 1990).

While surgery is certainly a recognized treatment for rotator cuff tears, not all surgical repairs are successful and tendons may re-rupture. The incidence of re-ruptures after arthroscopic (Galatz et al., 2004; Lafosse et al., 2007; Liu & Baker, 1994) or open (Gazielly et al., 1994; Harryman et al., 1991) repair of rotator cuff tears ranges from 11.4 % to 94%. The lowest rate of 11.4% (12 of 105) was reported in a series of 105 shoulders that underwent arthroscopic double row repair of supraspinatus or a combination of supraspinatus and infraspinatus (Lafosse et al., 2007). In contrast, Galatz et al. (2004) found recurrent tears to be as high as 94% (17 of 18) in arthroscopic repairs of massive tears at one year follow-up.

Currently, factors such as severity of tears, atrophy and fatty degeneration are used to determine the suitability for rotator cuff repair (Goutallier et al., 2003). However, patients with an identical diagnosis (i.e. full-thickness tears of the supraspinatus with the same amount of atrophy) can have significant variability in muscle contraction patterns (Boehm et al., 2005). Therefore, quantitative analysis of architectural parameters of a muscle that may have atrophy may allow the surgeons to detect if the muscle still has the potential to produce adequate forces.

To date, many studies have looked at the properties of tendon to explain the aetiology of tendon tears. However, aetiology may also be explained by changes in muscle architecture. Presently, changes in the rotator cuff muscle architecture as a result of surgical repair and its association with functional outcomes at different time points are not well understood and need to be investigated. Since the supraspinatus is most commonly injured structure in rotator cuff tears (Smith et al., 2000), a thorough understanding of its fiber architecture in normal and pathological states is necessary to understand the pathophysiology of rotator cuff tears.

1.6 Muscle Architecture

Muscle architecture is the arrangement of fiber bundles relative to the axis of force generation within a muscle (Lieber & Brown, 1992). The axis of force generation or the line of force is defined as the line to which the forces of contracted fiber bundles is projected (Lieber, 1993). The arrangement of fiber bundles can be grouped into either longitudinal or pennate arrangement. In muscles with longitudinal arrangement, fiber bundles are oriented parallel to the line of axis in a strap-like or fusiform manner, while the fibers are oriented at an angle to the line of axis in pennated muscles. Pennate muscles can be further categorized into unipennate, bipennate or multipennate.

Muscle architecture is characterised by fiber bundle length, pennation angle, physiological cross sectional area, muscle length and muscle volume. Architecture of the muscle essentially represents the complex arrangement of the sarcomeres within the muscle. The sarcomere is considered the functional unit of force production in a skeletal muscle. Therefore, these architectural parameters have a direct relationship with the contractile and functional properties of the muscle.

1.6.1 Fiber Bundle Length

Fiber bundle length (FBL) is one of the most important architectural parameters of a muscle, and is defined as the distance between the two attachment sites (origin and insertion) of one fiber bundle (Kim et al., 2007). Functionally, number of sarcomeres in series is proportional to the muscle's excursion and velocity (Gans, 1982). In a muscle, FBL reflects the number of sarcomeres in series. Thus, the longer the fiber bundles the more sarcomeres are in series and there is a greater shortening velocity of the muscle.

1.6.2 Pennation Angle

Pennation angle (PA) is the angle created by the fiber bundles with the line of the force (Murray et al., 2000). PA allows only a component of force to be projected onto the line of force; therefore, the force produced by the contraction of the fibers will be less than the total force of the individual fibers. On the contrary, PA permits greater number of fiber bundles to be packed in parallel for a given cross sectional area which increases the total force of muscle contraction (Gans & Bock, 1965). The end result is the combination of two factors. PA is often used in the calculation of physiological cross sectional area of pennated muscles.

1.6.3 Physiological Cross Sectional Area

Physiological cross sectional area (PCSA) is the sum of cross sectional areas of all the fibers in the muscle. PCSA represents the arrangement of sarcomeres in parallel, which is proportional to the force generation capacity of the muscle (Gans, 1982). Therefore, the more fibers in parallel (more PCSA), the more number of sarcomeres in parallel, and the greater the tension generated by the muscle.

1.6.4 Muscle Length

Muscle length (ML) is defined as "the distance from the origin of the most proximal muscle fibers to the insertion of the most distal fibers" (Mathewson et al., 2014; Ward et al., 2005). The ratio of FBL to ML may be used to compare excursion abilities of different muscles.

1.6.5 Muscle volume

The volume of the muscle is an important parameter and has been widely used in the calculations of PCSA. Muscle volume (MV) has also been found to be a major determinant of joint torque in humans (Fukunaga et al., 2001). These architectural properties vary between the skeletal muscles indicating different functions of the muscles.

1.6.6 Relevance of muscle architecture

Muscle architecture is clinically and functionally relevant. The clinical relevance of fiber architecture has been discussed in many previous studies. In an *in-vivo* US investigation study, the architecture of the supraspinatus muscle was not found to be uniform throughout the muscle volume. This variation in architectural parameters within the different regions of the muscle may result in sheer stress on the intramuscular tendon of the muscle and lead to tendon tears (Kim et al., 2010). In addition to improving our understanding of muscle function and pathology, muscle architecture may also provide important insight for making choices of muscles used for tendon transfer surgeries. Tendon transfers are surgical procedures in which distal tendons of the muscles are transferred from their normal point of anchorage to a different position. These surgeries are performed to correct any deformity and improve lost muscle function. It may be appropriate to select a donor muscle with similar and comparable architectural properties as the original muscle for tendon transfer surgeries to better perform the function of original muscle (Lieber & Fridén, 2001).

Architectural parameters of muscles form the basis of musculoskeletal and finite element models (Figure 1.2). In order to properly reflect a muscle's function using skeletal muscle models, an accurate representation of muscle geometry is needed. These musculoskeletal models provide insight into what is happening at the muscle level and have the potential to compute internal forces and simulate surgeries. Furthermore, these models can be used to gain insight into the associated post-operative functional outcomes. For example, using a biomechanical model, Magermans et al. (2004) evaluated the effect of different muscle tendon transfers to compensate the loss of rotator cuff force due to massive supraspinatus tendon tears in twenty-four healthy female subjects. They recorded the normal kinematics and muscle forces required to performing various activities of daily living using the shoulder in different ranges of motion. Then, similar simulations were performed using different models in which supraspinatus was not producing any force and tendon of latissimus dorsi or teres major alone or both in combination were transferred in the model to test the suitable muscle which can compensate for the loss of force. Based on the findings of the study, it was suggested that a tendon transfer of teres major alone or in combination with latissimus dorsi may be effective to repair large irreparable rotator cuff muscles (Magermans et al., 2004).

In summary, knowledge of the geometric arrangement of muscle fibers can provide insight into the muscle's function, mechanical basis of injury and may aid in optimizing rehabilitative and surgical protocols. Further explanations of these architectural parameters and the architectural findings from the previous studies have also been discussed in detail in the first manuscript of this thesis (page 21).

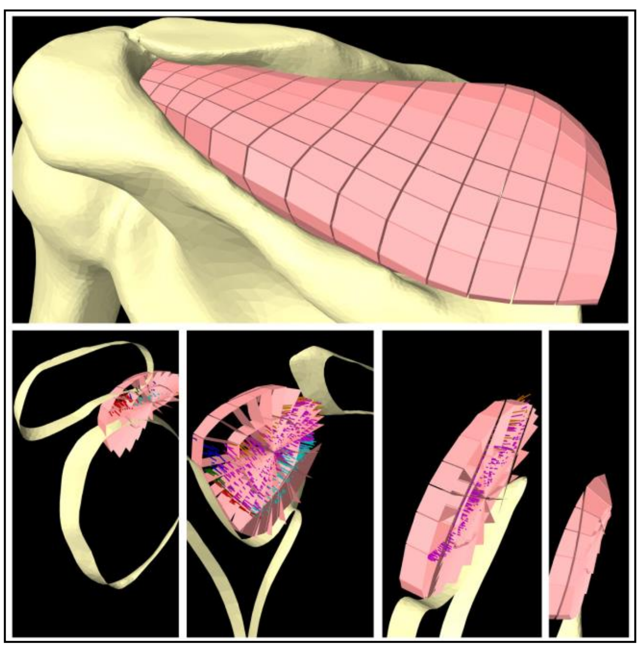

Figure 1.2: Three-dimensional fiber element supraspinatus model: posterior oblique view (top); axial cross-sections showing muscle fibers (bottom). Adapted from Stavness and Kim, 2013.

1.7 Ultrasound

The use of imaging modalities such as MRI, US and computed tomography (CT) is well established to studying the muscle architecture. Of these, US is used more often because it is portable, easy to use and inexpensive (Pillen & van Alfen, 2011). US is also non-invasive and a readily available imaging tool commonly used to investigate the skeletal muscle architecture. It enables direct visualization of skeletal muscle architecture in static and dynamic states. The reliability and/or validity of US has been documented in several muscle architectural studies (Chleboun et al., 2001; Ema et al., 2013; Kim et al., 2010). Juul-Kristensen et al. (2000) demonstrated that US is a valid method for measuring muscle thickness, cross sectional area, and moment arms of supraspinatus muscle. Morse et al. (2008) also found strong intra-rater correlation for FBL, PA and MV when measured from US scans of lateral gastrocnemius. Recently, Kim et al. (2010) developed and validated an US protocol to objectively quantify the supraspinatus architecture and found strong intra-rater and inter-rater correlations.

1.8 Summary of limitations in current knowledge

There have been many studies investigating the architecture of the normal and pathologic supraspinatus in the literature (Kim et al., 2010; Kim et al., 2013; Tomioka et al., 2009; Zuo et al., 2012). Of these studies, cadaveric studies are in abundance and provide most of the architectural data; however, most of these are descriptive in nature and have only focused on the gross morphology of the muscle (Aluisio et al., 2003; Keating et al., 1993). In order to understand the architectural changes of a normal muscle in response to strength training and the architecture of a pathologic muscle and the outcomes following surgical repair, it is necessary to first understand the architecture of a normal healthy muscle. Due to several limitations and variability in the reported data in previous cadaveric studies, the clinical relevance and potential for future application of the data remains unclear. In our view, there is a need to summarize the current state of knowledge regarding the architecture of the normal supraspinatus by systematically reviewing and critically evaluating the methodological quality of the available literature. The systematic review could serve as a useful resource for researchers and clinicians, and contribute to advancing future muscle architecture studies.

Architectural changes associated with tendon tears have several clinical implications. A change in FBL following an injury can affect the contraction velocity of the muscle and the range at which it operates with the joint movement, which are critical for rehabilitation and to perform surgical repair (Kim et al., 2013). To date, despite the high occurrence of supraspinatus tendon tears and volume of surgical repairs, there is a lack of information regarding the changes in the supraspinatus muscle architecture following surgical repair. Investigating the muscle architecture following surgical repair at different time intervals will advance the understanding of muscle recovery for rehabilitation professionals and surgeons, and allow them to better design and implement new treatment approaches.

Conservative management is the first line of treatment for rotator cuff tears (Pegreffi et al., 2011). Due to the high injury rate and important contribution the supraspinatus muscle provides for optimal shoulder function, its strengthening is an essential component of any rotator cuff rehabilitation program. There have been previous efforts to define an optimal exercise for the rehabilitation of supraspinatus using EMG and MRI (Blackburn et al., 1990; Reinold et al., 2004; Reinold et al., 2007; Takeda et al., 2002), but the results of the studies are variable. Since the muscle architecture is related to the function of the muscle, an in depth assessment of muscle architecture of supraspinatus following strengthening exercises may provide critical information that may help clinicians decide on exercise prescription for clients. To our knowledge, an *in-vivo* study that investigates the supraspinatus architecture following different exercises is yet to be published.

1.9 Research Objectives

Given the architectural complexity of the supraspinatus, the prevalence of supraspinatus injury and surgical repairs, and the critical role of rehabilitation for treating supraspinatus tendon tears, it is important to gain an in-depth understanding of the static and dynamic architecture of supraspinatus and the architectural changes associated with surgical repair and exercise training to improve surgical and rehabilitative treatment strategies for rotator cuff tears. The objectives of this dissertation were to: (1) synthesize the evidence on the quality of supraspinatus architectural studies and highlight the key aspects that should be considered while performing studies of skeletal muscle architecture, (2) understand the impact of surgical repair on the structural and functional recovery of the supraspinatus, and (3) provide a scientific rationale behind choosing an exercise to strengthen supraspinatus by investigating its muscle architecture. The objectives of this dissertation were addressed by the following specific objectives:

- Objective ‘1’ was addressed by conducting a systematic review of the human cadaveric studies of the normal supraspinatus architecture.

- Objective ‘2’ was addressed by quantifying and comparing the fiber bundle architecture of the pathologic supraspinatus pre- and post-operatively at multiple time points.
- Objective ‘3’ was addressed by comparing the efficacy of three commonly prescribed supraspinatus strengthening exercises in the rehabilitation setting based on the architectural changes following resistance training.

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CHAPTER TWO

ARCHITECTURAL PARAMETERS OF SUPRASPINATUS: A SYSTEMATIC REVIEW AND SYNTHESIS OF EVIDENCE

2 Manuscript #1

This manuscript was submitted to the special edition of Physical Therapy Reviews in October, 2014. It was revised and re-submitted again on February 03, 2015. When published, the citation of the manuscript will be as follows:

Rohit Sachdeva, Angela Jean Busch, Elizabeth Louise Harrison, Julia Bidonde, Soo Young Kim. Architectural parameters of the supraspinatus: A systematic review of cadaveric studies. Physical Therapy Reviews [Year], [Issue], [pages].

This manuscript systematically reviewed and assessed the quality of 18 human cadaveric studies on the architecture of normal supraspinatus. Systematic reviews always involve more than one person and require at least two independent reviewers for screening and selecting studies, extracting data and assessing the quality of studies. As mentioned in the preface, this manuscript was prepared through collaborative team work; however, the graduate student researcher (RS) was the lead author in this manuscript.

Contribution of authors:

RS: developing search strategy, designing study selection criteria, screening studies, data extraction, designing the quality assessment checklist and assessing the quality of studies, data analysis, writing and reviewing manuscript, ongoing editing of manuscript, approving the final draft of the manuscript and training another reviewer.

AB: designing the protocol for review, developing study selection criteria and quality assessment checklist, reviewing drafts and approving the final draft of the manuscript

ELH: reviewing drafts and approving the final draft of the manuscript

JB: designing study selection criteria, reviewing drafts and approving the final draft of the manuscript

SYK: designing the protocol for review, designing the quality assessment checklist, reviewing drafts and approving the final draft of the manuscript.

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This manuscript is presented in the form in which it was submitted for publication with the exception of some minor changes necessary for the conversion to graduate thesis format.

Title: Architectural parameters of supraspinatus: A systematic review of cadaveric studies.
Background: Architectural parameters of skeletal muscles directly inform us on the functional capabilities of the muscle and are critical for understanding joint biomechanics. The supraspinatus is most commonly implicated with shoulder pathology. Thus, the more robust and accurate the data is of this muscle, the better we can advance the treatment strategies.
Objectives: To systematically review human cadaveric studies of the normal supraspinatus architecture.
Methods: Electronic databases MEDLINE, EMBASE, CINAHL and SCOPUS were searched to identify articles describing the architectural parameters of the normal supraspinatus in human cadaveric specimens. The quality of the studies was evaluated using a checklist composed of eight factors.
Results: Eighteen studies were included with the overall quality found to be low in 12. Only two studies calculated the detailed architecture of distinct regions of the muscle. The number and location of fiber bundles sampled was documented in five and four studies respectively. There was a large range in the reported architectural values of the entire muscle: fiber bundle length, 2.8 to 11.7 cm; pennation angle, 0 to 11.4 degrees; muscle volume, 23 to 37 cm^3; and physiological cross sectional area, 2.48 to 7.51 cm^2.
Conclusions: There is significant variation in reported architectural values for supraspinatus with only a few studies providing the level of detail and quality suitable for advancing our understanding of shoulder biomechanics. The critical factors identified in the review may guide and improve the quality of future skeletal muscle architectural studies.

2.1 Introduction

The clinical importance of the supraspinatus has been emphasized since the initial works of Codman, who recognized the prevalence and importance of supraspinatus tendon ruptures (Codman, 1938). Unfortunately, supraspinatus injury remains one of most common causes of shoulder pain and functional deficit (Yamamoto et al., 2010). In a prospective study of 191 patients with rotator cuff tears, Smith et al. (2000) found tears of supraspinatus in 190 of the patients. To advance biomechanical assessments and treatment techniques for pathologies involving supraspinatus, a thorough understanding of the normal skeletal muscle architecture and function is crucial. Despite the clinical relevance, few studies have investigated the normal muscle architecture of the entire supraspinatus.

Skeletal muscle architecture is a major determinant of the functional properties of a muscle and is defined as the arrangement of fibers within its volume (Lieber & Brown, 1992; Lieber & Fridén, 2001). Accurate knowledge of skeletal muscle architecture is important for understanding complex joint biomechanics and developing reliable finite-element models of the musculoskeletal system. These models, in turn, provide insight into muscle function under various loading conditions and can also assist in improving clinical decision making and predicting functional outcomes following surgery.

Specific architectural parameters that can influence the muscle function include muscle fiber bundle length, physiological cross sectional area, pennation angle, muscle volume and muscle length. Muscle fiber bundle length (FBL) and physiological cross sectional area (PCSA) are the best predictors of a muscle's excursion velocity and force generating capacity respectively (Gans, 1982). Muscle volume (MV) and pennation angle (PA) also influence the contractile properties of the muscle, and are commonly used to estimate the PCSA of a muscle.

The supraspinatus muscle is architecturally and functionally complex (Kim et al., 2007; Vahlensieck et al., 1994). The muscle belly which lies in the supraspinous fossa of the scapula is composed of two distinct regions: anterior and posterior (Kim et al., 2007; Roh et al., 2000; Vahlensieck et al., 1994). The tendon of supraspinatus has both intra- and extra-muscular portions laterally, and inserts on the superior facet of greater tubercle of the humerus (Drake et al., 2009). The supraspinatus is commonly known to be a stabilizer of the glenohumeral joint which provides a compressive force to prevent excessive humeral head translation when it works in conjunction with other rotator cuff muscles (Halder et al., 2001; Moore et al., 2002;

Thompson et al., 1996). [11-13] It also contributes to the abduction of the glenohumeral joint (Thompson et al., 1996). Based on several electromyographic and biomechanical studies, the supraspinatus muscle has also been characterised as an external rotator of the shoulder joint (Boettcher et al., 2009; Gates et al., 2010; Ihashi et al., 1998). The function of the anterior and posterior regions of supraspinatus has been investigated in cadaveric and imaging studies (Kim et al., 2007; Kim et al., 2010; Roh et al., 2000). Based on the PCSA (Roh et al., 2000), MV (Kim et al., 2007), in-vivo investigation of dynamic fiber bundle changes (Kim et al., 2010) and fiber types (Kim et al., 2013), the anterior region is thought to produce most of the force while the posterior region quickly adjusts tension on the tendon.

The force generating properties of muscles used for modelling purposes are often derived from cadaveric studies of muscle architecture. Although imaging techniques such as magnetic resonance imaging (MRI) and computed tomography (CT) have been used to volumetrically reconstruct skeletal muscles (Blemker & Delp, 2005), it has not been possible to obtain detailed internal fiber architecture of a muscle throughout its volume. Therefore, with advances in computer modelling, which are dependent on information obtained from cadaveric studies, a systematic review of the current state of knowledge of the supraspinatus muscle architecture is needed.

To our knowledge, shoulder muscle architectural reviews, in particular the supraspinatus, have not been conducted to date. Also, we are not aware of any publication discussing or presenting the critical methodological factors needed to be considered while investigating skeletal muscle architecture. Therefore, the purpose of this review was to systematically review human cadaveric studies of the normal supraspinatus architecture.

2.2 Methods

The preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines (Moher et al., 2009) and the five essential features of systematic reviews described by the Cochrane handbook for systematic reviews of intervention (Higgins & Green, 2011) were used to design the methodology of the paper. The study selection, article screening, data extraction and quality assessment of the included studies were performed independently by two reviewers (RS and GS) and any disagreement was resolved through consensus. A third reviewer (SK) was also available for consultation in the event of disagreement but this was not needed.

2.2.1 Search Strategy

The following four electronic databases were searched without any limitations being set: MEDLINE (1950- March 2014), EMBASE (1947- March 2014), CINAHL (1937- March 2014) and SCOPUS (1996- March 2014). The references of retrieved articles were also searched manually for additional citations. Searches were conducted using the following search terms: *morphology, architecture, structure, fibre/fiber/fascicle length, pennation angle, physiological cross sectional area, muscle volume, muscle length, shoulder, supraspinatus, rotator cuff, and cadavers* with sensible Boolean operators (see Appendix 1 for Medline search strategy).

2.2.2 Study Selection

Following the search, the screening of titles and abstracts of the retrieved articles was undertaken (Appendix 2). Full-text publications of selected abstracts were assessed to determine if they met the inclusion criteria. The inter-rater agreement for article inclusion was calculated using Kappa statistics (κ). The analysis was done with SPSS (version 20; SPSS Inc., Chicago, IL, USA) statistical software and the strength of agreement between the raters was interpreted according to Landis and Koch (Landis & Koch, 1977): value of < 0.00 = Poor, 0.00-0.20= Slight, 0.21-0.40 = Fair, 0.41-0.60 = Moderate, 0.61-0.80 = Substantial and 0.81-1.00 = Almost Perfect.

2.2.3 Data extraction

The following data were extracted independently by the two reviewers: 1) study and specimen characteristic: author(s), year of publication, purpose(s) of the study, number of supraspinatus specimens studied, mean age and gender of the specimens; and 2) architectural findings: values of supraspinatus architectural parameters investigated, number of fiber bundles sampled. Due to time constraints, authors of included studies were not contacted for missing data.

2.2.4 Quality Assessment

Included studies were assessed for quality using a checklist specifically developed for this review based on critical factors identified by the reviewers that could influence the description of muscle architecture. The checklist composed of eight items is as follows:

1. Was the age of specimens specified?
2. Was the gender of specimens specified?
3. Was the sample size based on power analysis?
4. Were all measurement parameters clearly defined?

5. Were the locations of measurements clearly specified?

6. Was the number of fiber bundles sampled for fiber bundle length and/or pennation angle defined?

7. Was the instrumentation used to measure all parameters specified?

8. Was the reliability of measures reported?

Each item in the checklist was assigned one point and the overall score for each study was converted to a percentage by averaging the total score and multiplying it by 100. We then classified studies into three categories: low, moderate and high quality, using arbitrary groupings (Busch et al., 2008) of 0-49% for low quality, 50-74% for moderate quality and 75-100% for high quality. Any disagreement was resolved through discussion. A third reviewer was available to arbitrate in the event of disagreement, but was not needed. The method and interpretation used to assess inter-rater agreement for study selection was used to calculate the inter-rater agreement on the use of the quality assessment checklist.

2.2.5 Data Synthesis

A detailed inspection of included studies was undertaken and the findings for each architectural parameter were recorded to make comparisons. Although meta-analysis was not performed because of the heterogeneous nature of the studies and insufficient details on the characteristics of the specimens, number and location of fiber bundles sampled and differences in methodologies, quality of the selected studies was assessed using a specially designed checklist.

2.3 Results

2.3.1 Search Results

The electronic search yielded 2326 articles and three articles were retrieved through manual search (see Figure 2.1). After eliminating duplicated articles, the remaining 1191 articles were further screened based on the inclusion criteria. Following title and abstract screening, 62 full-text articles were identified. Of those, 18 studies were assessed as meeting the inclusion criteria. The inter-rater agreement for article inclusion was found to be substantial ($\kappa = 0.67$). Most of the excluded studies did not investigate with the normal supraspinatus muscle and/or investigated less than five specimens. One study (Howell et al., 1986) was excluded because of the unclear methodology.

2.3.2 Study and Specimen Characteristics

Table 2.1 outlines the study and specimen characteristics of the selected studies. Of the included studies, eight were published between 1991 and 2000 and ten between 2001 and March 2014. There was a wide variation in the purposes of the studies ranging from quantification of supraspinatus muscle architecture to developing a three-dimensional musculoskeletal model of the shoulder. The number of specimens varied from 5 to 49 between the studies. A total of 242 supraspinatus muscle specimens were assessed for muscle architecture in 18 studies. The age of the specimens varied from 17 to 97 years, with five studies not reporting the age values (Johnson et al., 1996; Keating et al., 1993; Langenderfer et al., 2006; Mathewson et al., 2014; Zuo et al., 2012). In one study (Itoi et al., 1995), it was not possible to differentiate the age of normal cadaveric specimens from that of pathologic specimens. Of the studies which clearly defined the gender of the specimens, 72 were male and 63 were female. The gender of the specimens was not documented in seven studies (Aluisio et al., 2003; Itoi et al., 1995; Johnson et al., 1996; Keating et al., 1993; Mathewson et al., 2014; Peterson & Rayan, 2011; Zuo et al., 2012) and in one study (Vahlensieck et al., 1994) the number of male and female specimens in the total number of specimens investigated was not clearly stated.

2.3.3 Architectural Findings

The architectural findings of the normal supraspinatus from human cadaveric studies are presented in Table 2.1. The mean FBL of entire muscle was computed in 9 of 18 studies (Aluisio et al., 2003; Herzberg et al., 1999; Itoi et al., 1995; Juul-Kristensen et al., 2000; Keating et al., 1993; Mathewson et al., 2014; Peterson & Rayan, 2011; Tomioka et al., 2009; Ward et al., 2006) and ranged from 2.8 (Itoi et al., 1995) to 11.7 (Peterson & Rayan, 2011) cm. In some studies, FBL was measured as the distance between the origin and insertion of individual fiber bundles (Herzberg et al., 1999; Keating et al., 1993; Kim et al., 2007; Tomioka et al., 2009). Yet in another study (Aluisio et al., 2003) multiple methods were used. First, the FBL was measured from proximal-most origin to proximal-most insertion; second, from distal-most origin to distal-most insertion; third, they used "direct method"; and fourth, they removed the muscle in its entirety and measured the FBL independent of joint position. Mean FBL was calculated by pooling and averaging the data obtained from these methods. In four studies, the mean FBL was normalized to scapular length (Itoi et al., 1995) or sarcomere length (Langenderfer et al., 2006; Mathewson et al., 2014; Ward et al., 2006). The number of fiber bundles sampled for FBL measurement was either very low (Juul-Kristensen et al., 2000; Tomioka et al., 2009) or not specified (Herzberg et al., 1999; Keating et al., 1993; Langenderfer et al., 2006; Mathewson et al., 2014; Peterson & Rayan, 2011; Roh et al., 2000; Ward et al., 2006). Mean FBL of anterior and posterior regions were reported in two studies (Kim et al., 2007; Roh et al., 2000). In one study (Ward et al., 2006), although the different regions of the muscle were recognized, an average value of FBL was provided for the entire muscle. Kim et al. (2007) further calculated the FBL of different sub-regions of anterior and posterior regions. In five studies (Langenderfer et al., 2006; Mathewson et al., 2014; Roh et al., 2000; Tomioka et al., 2009; Ward et al., 2006), digital or precision calipers were used while in others (Aluisio et al., 2003; Herzberg et al., 1999; Itoi et al., 1995; Juul-Kristensen et al., 2000; Keating et al., 1993; Peterson & Rayan, 2011), the instrumentation used to measure FBL was not specified.

Of the included studies, 8 calculated PA of the supraspinatus (Juul-Kristensen et al., 2000; Kim et al., 2007; Langenderfer et al., 2006; Mathewson et al., 2014; Peterson & Rayan, 2011; Roh et al., 2000; Ward et al., 2006; Zuo et al., 2012). The mean PA reported for the entire muscle ranged from 0 (Peterson & Rayan, 2011) to 11.4 (Juul-Kristensen et al., 2000) degrees. Two studies provided the PA values of anterior and posterior regions separately (Kim et al., 2007; Roh et al., 2000) and one study reported the PA of anterior region of the muscle (Zuo et al., 2012). Kim et al. (2007) further calculated the PAs of the superficial, middle and deep parts of the anterior and posterior regions. Based on the medial and lateral attachment sites of fiber bundles, they computed the medial and lateral PAs of both distinct regions and their respective parts. To compute PA, in four studies (Mathewson et al., 2014; Peterson & Rayan, 2011; Roh et al., 2000; Ward et al., 2006), a goniometer was used while in others computer algorithms (Kim et al., 2007) and imaging software (Zuo et al., 2012) were used. In one study (Juul-Kristensen et al., 2000) instrumentation was not specified at all.

Seven studies assessed the MV of the supraspinatus (Aluisio et al., 2003; Itoi et al., 1995; Juul-Kristensen et al., 2000; Keating et al., 1993; Kim et al., 2007; Roh et al., 2000; Tingart et al., 2003). The mean MV of the entire supraspinatus muscle belly has been reported to range from 23 (Keating et al., 1993) to 37 (Tingart et al., 2003) cm^3. As with FBL and PA, Roh et al. (2000) and Kim et al. (2007) were the only studies to report separate volume measurements for the anterior and posterior regions of the muscle. The anterior region was found to be substantially greater in both the studies compared to the posterior region. The MV was calculated using fluid displacement method (Itoi et al., 1995; Juul-Kristensen et al., 2000; Keating et al., 1993; Roh et al., 2000; Tingart et al., 2003) or muscle mass and density values (Aluisio et al., 2003; Peterson & Rayan, 2011; Ward et al., 2006). However, in one study (Tingart et al., 2003), MRI was used to evaluate MV.

The PCSA of supraspinatus was investigated in 12 of the studies (Aluisio et al., 2003; Herzberg et al., 1999; Itoi et al., 1995; Johnson et al., 1996; Juul-Kristensen et al., 2000; Keating et al., 1993; Langenderfer et al., 2006; Mathewson et al., 2014; Peterson & Rayan, 2011; Roh et al., 2000; Veeger et al., 1991; Ward et al., 2006). The mean PCSA values of the entire muscle ranged from 2.48 (Peterson & Rayan, 2011) to 7.51 (Mathewson et al., 2014) cm^2. Roh et al. (2000) found the anterior region of the muscle belly to have a PCSA of 1.40 ± 0.44 cm^2 and the posterior region to have a PCSA of 0.62 ± 0.25 cm^2. In six studies (Aluisio et al., 2003; Herzberg et al., 1999; Itoi et al., 1995; Johnson et al., 1996; Keating et al., 1993; Langenderfer et al., 2006), PA was not included in the calculation of PCSA and was simply calculated by dividing muscle volume by FBL or optimal FBL (PCSA=MV/FBL). The mean PCSA was calculated using FBL, MV and/or PA in most of the studies. Only four studies (Mathewson et al., 2014; Peterson & Rayan, 2011; Roh et al., 2000; Ward et al., 2006) were found to include PA in the PCSA formula for the supraspinatus (PCSA=MV/FBL X PA).

Muscle Length (ML) was measured only in six studies (Langenderfer et al., 2006; Mathewson et al., 2014; Peterson & Rayan, 2011; Vahlensieck et al., 1994; Volk & Vangsness, 2001; Ward et al., 2006). The mean ML of the entire muscle ranged from 8.5 (Ward et al., 2006) to 14.5 (Volk & Vangsness, 2001) cm. Vahlensieck et al. (1994) measured the ML of the anterior and posterior regions and found it to be 10.6 *cm* and 8.9 cm respectively.

2.3.4 Quality Assessment

The results of the quality assessment are summarized in Table 2.2. The analysis of inter-rater agreement indicated that there was almost perfect agreement ($\kappa = 0.87$) between the raters on the use of quality assessment tool for the 18 included studies. Four studies (Tingart et al., 2003; Vahlensieck et al., 1994; Veeger et al., 1991; Volk and Vangsness, 2001) for which checklist items were not applicable, such as number of fiber bundles sampled and the location of measurements, were grouped separately for comparison purposes. Twelve studies were classified as low quality (Aluisio et al., 2003; Itoi et al., 1995; Johnson et al., 1996; Juul-Kristensen et al., 2000; Keating et al., 1993; Langenderfer et al., 2006; Mathewson et al., 2014; Peterson and

Rayan, 2011; Roh et al., 2000; Vahlensieck et al., 1994; Veeger et al., 1991; Volk and Vangsness, 2001), three as moderate quality (Herzberg et al., 1999; Ward et al., 2006; Zuo et al., 2012) and three as high quality (Kim et al., 2007; Tingart et al., 2003; Tomoika et al., 2009). The age and gender of the specimens were poorly defined in majority of the studies regardless of their quality. The sample size was low in many studies and was not justified by power analysis in any study. Given the architectural variation with the depth of the muscle (Fung et al., 2009; Kim et al., 2007), only four studies (Kim et al., 2007; Tomioka et al., 2009; Ward et al., 2006; Zuo et al., 2012) described the location at which measurements were taken. The number of fiber bundles sampled for FBL and/or PA measurements were clearly stated in five studies (Aluisio et al., 2003; Herzberg et al., 1999; Kim et al., 2007; Tomioka et al., 2009; Zuo et al., 2012). Sampling of fiber bundles was not applicable for four studies which did not evaluate FBL and/or PA (Tingart et al., 2003; Vahlensieck et al., 1994; Veeger et al., 1991; Volk & Vangsness, 2001). Furthermore, the majority of studies lacked a clear definition of architectural parameters, how the measurements were taken and/or information on the measurement instrumentation. Reliability of measures, an important psychometric property demonstrating reproducibility of measurements, was presented only in one study (Tingart et al., 2003).

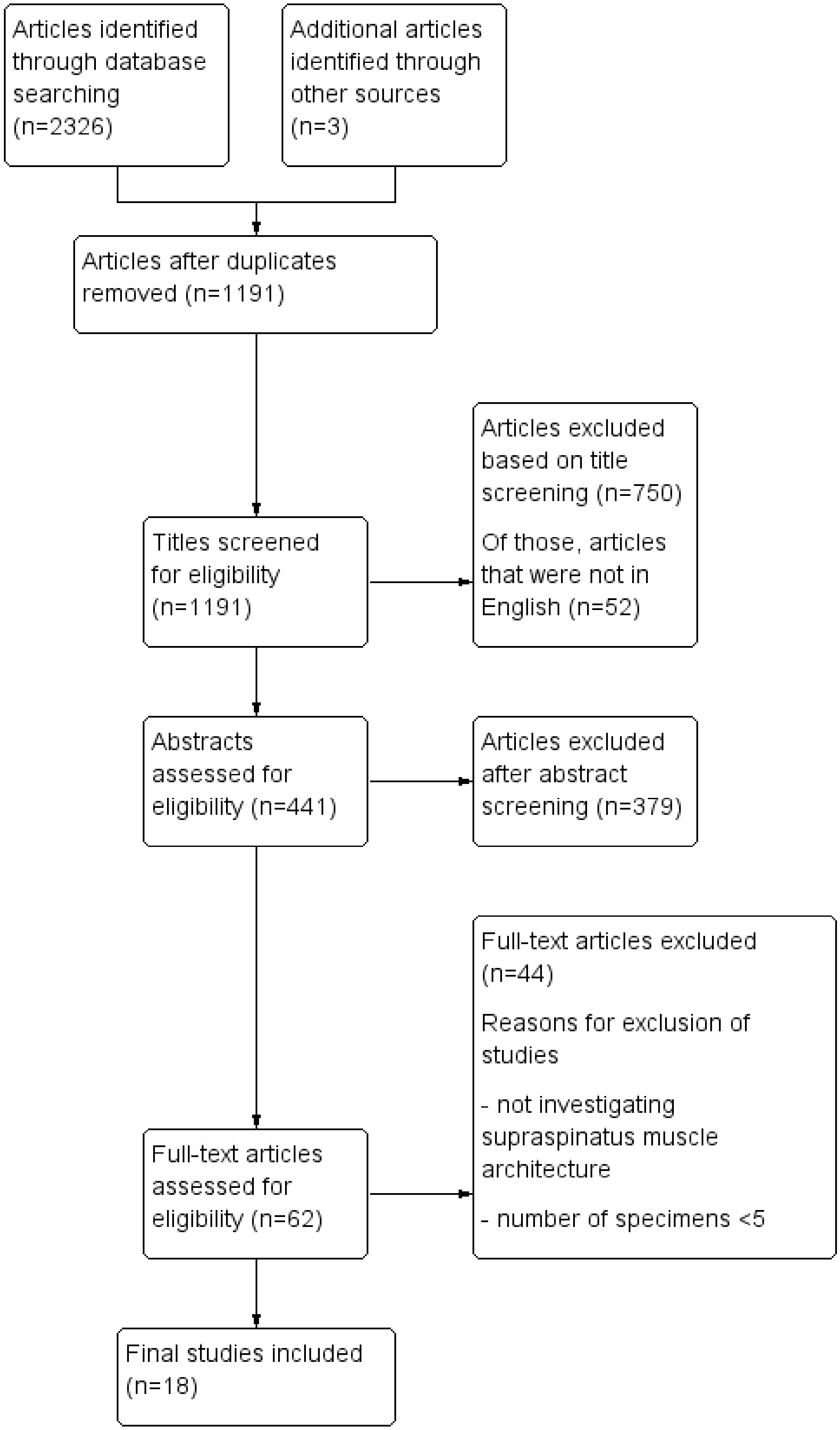

Figure 2.1 Prisma flow chart

Table 2.1 Study and specimens' characteristics and architectural findings of normal supraspinatus muscle

Author	Purpose	Number of specimens/ gender	Mean age of specimens (range) in years)	Part of muscle	Muscle Length (*cm*)	Muscle Volume (cm^3)	Pennation Angle (degrees)	Number of fiber bundles sampled for fiber bundle length and/or pennation angle measurements	Fiber Bundle Length (cm)	Physiological Cross Sectional Area (cm^2)
Veeger et al. (1991)	To develop a musculoskeletal model of the shoulder mechanism and obtain a complete set of parameters.	14 (10M:4F)	80 (70-90)	___	___	___	___	___	___	5.21 ± 1.76
Keating et al. (1993)	To quantify the force generating capability and define the contribution of rotator cuff muscles to the moment generated about the glenohumeral joint.	5 (___)	___	___	___	23 (15-31)	___	___	5.6 (4.7-6.5)	4.02 (3.2-5.2)
Vahlensieck et al. (1994)	To analyze the fibrous architecture of supraspinatus and its relationship to the scapula in cadaver dissections and on MRI.	49 (15M and 15F)	52-97	Anterior Posterior	10.6 ± 2.37 8.9 ± 1.34	___	___	NA	___	___
Itoi et al. (1995)	To determine the effect of rotator cuff tear on the morphology of the cuff and its associated structures and to consider the possible functional consequences.	11 (___)	64-96 years (normal and pathologic)	___	___	30.5 ± 12.7	___	___	2.78 ± 0.5 (normalized)	7.1 ± 3.6[a]
Johnson et al. (1996)	To present morphological data on the major muscles of the scapula, as a new and more detailed contribution to these engaged in the development of biomechanical models.	6 (___)	NR	___	___	___	___	___	___	3.0
Herzberg et al. (1999)	To provide a list of the capabilities of the various shoulder girdle muscles in terms of potential excursion and relative tension that could be consulted during consideration of musculotendinous transfer around the shoulder.	13 (7M:6F)	74 (17-89)	___	___	___	___	3	6.7 ± 0.6	5.2 ± 0.8[b]
Juul-Kristensen et al. (2000)	1) To test the reliability and the validity of the MRI-scanning method. 2) To quantify muscle sizes and moment arms of rotator cuff muscles of females in order to improve the quality of the parameters used in biomechanical shoulder models and furthermore to test selected external anthropometric measures as predictors of muscle sizes and moment arms.	9 (F)	78.9 (55-87)	___	___	29.7 ± 11.6	11.4 ± 7.8	___	4.7 ± 1.1	6.6 ± 2.6

Roh et al. (2000)	1) To elucidate the form-function relationship of the supraspinatus. 2) To describe both qualitatively and quantitatively the musculotendinous anatomy of the anterior and posterior supraspinatus.	25 (10M:15F)	82	Anterior	___	12 ± 4 (7-25)	14 ± 3 (8-20)	NR	8.33 ± 0.88 (4.47-11.72)	1.40 ± 0.44 (0.77-2.52)
				Posterior		4 ± 2 (1-8)	10 ± 3 (2-20)		6.54 ± 1.2 (3.47-10.08)	0.62 ± 0.25 (0.27-1.17)
Volk and Vangsness (2001)	To examine the lateral gross and histomorphologic features of the lateral supraspinatus muscle and tendon.	20 (10M:10F)	48-76	___	14.5 (12.2- 16.8)	___	___	NA	___	___
Aluisio et al. (2003)	To define the muscular force and moment relations across the glenohumeral joint.	5 (NR)	60-78	___	___	32.1 (26.1-39.9)	___	20	6.06 (5.5-6.3)	5.26 (4.7-6.3)
Tingart et al. (2003)	To determine the reliability and validity of MRI in quantitative assessment of rotator cuff muscle volumes.	10 (4M:6F)	76 (67-82)	___	___	37 ± 12 36 ± 12 (MRI)	___	NA	___	___
Langenderfer et al. (2006)	To determine a complete dataset of muscle-tendon parameters suitable for predicting the force generating capacity of the sub-regions of infraspinatus, supraspinatus and teres minor muscles.	10 (7M:3F)	___	Anterior[c]	10.6 ± 1.6	___	10 ± 4.3	___	7.5 ± 1.5	1.36 ± 0.40
				Middle	12.4 ± 2.1		12 ± 6.4		8.4 ± 1.5	1.27 ± 0.34
				Posterior	11.8 ± 1.8		11 ± 3.5		8.3 ± 1.3 (normalized)	0.97 ± 0.40
Ward et al. (2006)	1) To determine if muscle fiber length and physiological cross-sectional area differed between the rotator cuff muscles. 2) To estimate the sarcomere length-joint angle relationships of each muscle to predict the contribution of each muscle to shoulder function as a function.	10 (5M:5F)	89 ± 12	Anterior Posterior	8.5 ± 0.4[d]	___	5.1 ± 0.8[d]	___	4.50 ± 0.32[d] (normalized)	6.65 ± 0.56[d]
Kim et al. (2007)	To investigate and quantify the three-dimensional musculotendinous architecture of supraspinatus throughout its volume.	10 (M)	61.9 ± 16		___		Lateral / Medial	1200-1600/specimen		___
				Anterior		15.4 ± 5.7				
				• Superficial			60.0 ± 12 / 11.8 ± 2.7		6.7 ± 0.7	
				• Middle			64.6 ± 12.7 / 11.4 ± 2.8		6.7 ± 0.5	
				• Deep			51.4 ± 13.1 / 9.8 ± 2.3		6.6 ± 0.6	
							74.1 ± 10.2 / 16.8 ± 6.1		6.6 ± 0.6	
				Posterior		2.5 ± 0.7	82.8 ± 4 / 12.4 ± 3.6		6.7 ± 0.5	
				• Superficial			84.4 ± 3.1 / 18.6 ± 7.6		6.9 ± 0.9	
				• Middle			82.0 ± 4.3 / 11.3 ± 4.6		7.0 ± 0.6	
				• Deep			82.5 ± 4.9 / 11.2 ± 3.6		6.2 ± 0.5	
Tomioka et al. (2009)	To clarify the sarcomere length of intact and torn rotator cuff muscles of human cadaveric shoulders.	14 (9M:5F)	80 (63-91)	___	___	___	___	3	5.69 ± 1.01	___

Peterson and Rayan (2011)	To examine the architecture of the shoulder and upper arm muscles and generate data that could serve as a guide for comparison, compatibility, and relative performance among these muscles for use in transfer.	9 (____)	73	____	12.7 ± 0.7	____	0	____	11.7 ± 0.7	2.48 ± 0.94
Zuo et al. (2012)	1) To determine the changes in pennation angle that occurred after rotator cuff tears in human cadaveric shoulders. 2) To clarify the relationship between the pennation angle of rotator cuff muscles and the size of tendon tears.	10 (____)	____	Anterior	____		10.2 ± 2.3	10	____	____
Mathewson et al. (2014)	1) To define the architecture of each of the four rotator cuff muscles among humans and 10 species commonly used in rotator cuff research to determine the best models for healthy human rotator cuff. 2) To determine how rotator cuff muscle architecture scales with body size.	12 (____)	____	____	11.12 ± 0.28 (normalized)	____	7.98 ± 1.33	____	5.65 ± 0.28 (normalized)	7.51 ± 0.85

Male (M), Female (F), Magnetic resonance imaging (MRI), ± standard deviation (range), not applicable (NA), ---- data not collected/provided
[a]cross sectional area calculated as PCSA in other studies
[b]physiological cross sectional area expressed as percentage of a group of muscles
[c]regions were not defined based on architectural differences within the muscle
[d]values are averaged for anterior and posterior regions
All the data are mean ± standard deviation (except where indicated)

Table 2.2 Critical factors that influence the muscle architecture: quality assessment of the selected studies

Author(s)	Age of specimens clearly specified	Gender of specimens clearly specified	Sample size based on power analysis	All measurement parameters clearly defined	Location of measurements clearly specified	Number of fiber bundles sampled for fiber bundle length and/or pennation angle measurements clearly stated	Instrumentation used for measuring all parameters specified	Reliability of measures assessed	Total	Percentage (%)
Keating et al. (1993)	N	N	N	Y	N	N	N	N	1/8	12.5
Itoi et al. (1995)	N	N	N	Y	N	N	N	N	1/8	12.5
Johnson et al. (1996)	N	N	N	Y	N	N	Y	N	2/8	25
Herzberg et al. (1999)	Y	Y	N	Y	N	Y	N	N	4/8	50
Juul-Kristensen et al. (2000)	Y	Y	N	N	N	N	N	N	2/8	25
Roh et al. (2000)	Y	Y	N	N	N	N	Y	N	3/8	37.5
Aluisio et al. (2003)	Y	N	N	N	N	Y	N	N	2/8	25
Langenderfer et al. (2006)	N	Y	N	N	N	N	Y	N	2/8	25
Ward et al. (2006)	Y	Y	N	Y	Y	N	N	N	4/8	50
Kim et al. (2007)	Y	Y	N	Y	Y	Y	Y	N	6/8	75
Tomioka et al. (2009)	Y	Y	N	Y	Y	Y	Y	N	6/8	75
Peterson and Rayan (2011)	Y	N	N	N	N	N	N	N	1/8	12.5
Zuo et al. (2012)	N	N	N	Y	Y	Y	Y	N	4/8	50
Mathewson et al. (2014)	N	N	N	N	N	N	N	N	0/8	0
Veeger et al. (1991)	Y	Y	N	N	N	NA	Y	N	3/7	42.9
Vahlensieck et al. (1994)	Y	N	N	N	NA	NA	N	N	1/6	16.7
Volk and Vangsness (2001)	Y	Y	N	N	NA	NA	N	N	2/6	33.3
Tingart et al. (2003)	Y	Y	N	Y	NA	NA	Y	Y	5/6	83.3

Y=Yes=1, N=No=0, NA= not applicable

2.4 Discussion

To our knowledge, this is the first systematic review summarizing the architectural parameters of the normal supraspinatus obtained through human cadaveric dissection and assessing the methodological quality of the existing literature. This review helps to identify knowledge gaps and stimulates reflection on factors that might alter the clinical applicability of data.

2.4.1 Study and Specimen Characteristics

This review has included a growing body of research, as all included studies have been published since 1990. The size of a sample should be carefully taken into consideration while studying the muscle architecture. Recently, Tuttle et al. (2012) demonstrated a method to calculate sample size for human cadaveric dissection studies based on the calculation of fiber length coefficient of variation. They also recommended the inclusion of 10 or more specimens for human cadaveric muscle architectural studies. In order to generate confidence intervals and to avoid variability in reported architectural properties, larger sample sizes defined by power analysis are desirable (Tuttle et al., 2012). Inadequate description and reporting of the specimen characteristics created difficulties to draw comparisons and make generalizations from the reported data.

The muscle architecture of older specimens is likely to be different from that of younger specimens. Narici et al. (2003) investigated the effect of aging on human muscle architecture and found a significant reduction in the MV, anatomical cross sectional area, FBL and PA of the gastrocnemius medialis muscle in the older individuals compared to younger adults. They also reported a reduction in PCSA in the elderly group as a result of decreased MV and FBL (PCSA= MV/FBL). Gender based differences in muscle architecture have also been reported in literature (Chow et al., 2000). In an ultrasound study, overall, the soleus and gastrocnemius muscles of males were found to have shorter fibers, larger PAs and greater MT. Conversely, soleus and gastrocnemius muscles of females had longer fibers, smaller PAs and are not as thick as male muscle (Chow et al., 2000). Therefore, it is important to describe the age and gender of the specimens as these factors are directly linked to muscle performance.

2.4.2 Fiber Bundle Length

Fiber bundle length is defined as the distance between the origin and insertion of a fiber bundle and plays a significant role in determining force-length properties of a muscle (Lieber & Fridén, 2001). The FBL data of supraspinatus available from cadaveric studies is limited due to several issues. First, there was substantial variability in the methods used to measure FBL in this body of literature. Aluisio et al. (2003) used multiple methods to measure mean FBL. Based on descriptions, however, it was difficult to understand them and the rationale for choosing these different methods particularly the 'direct method' in which the proximal and distal ends were unclear. In addition to various methods used to measure FBL, only a few studies normalized the FBL measurements by the ratio of optimal sarcomere length to the mean measured sarcomere length (Langenderfer et al., 2006; Mathewson et al., 2014; Ward et al., 2006). The process of normalization allows for FBL comparisons between muscles regardless of the variation in FBL due to the joint angle or any stretch to the muscle during fixation (Ward et al., 2009). Itoi et al. (1995) normalized the FBL with scapular length which would not account for changes in the length of fiber bundles due to stretching.

Second, the locations of FBL measurements were often not reported. Most of the studies relied on superficially sampled fiber bundles for FBL measurements which limited them in describing the architectural variance at different depths within the muscle. As previously discussed, the supraspinatus has two architecturally and functionally distinct regions based on the lateral attachment of fiber bundles onto the tendon (Kim et al., 2007; Roh et al., 2000); therefore, specifying the exact lateral fiber bundle attachment to the anterior or posterior tendon is important. In the majority of the studies reviewed, however, the origin was not clearly outlined (Herzberg et al., 1999; Itoi et al., 1995; Juul-Kristensen et al., 2000; Mathewson et al., 2014; Peterson & Rayan, 2011). For example, Juul-Kristensen et al. (2000) calculated FBL on both sides of the "central tendon". The central tendon is likely the intramuscular portion of the tendon, thus, a measurement of the anterior region.

Third, the number of fiber bundles sampled for FBL measurements was very low. Because of the complexity of the muscle, sampling of a large number of fiber bundles is recommended to generate accurate data sets. A high fidelity data set can be used to better elucidate the functional properties of the muscle, and to develop a muscle model that will result in more accurate predictions of shoulder loading. More recently, architectural parameters of supraspinatus have been quantified using three-dimensional computer modelling techniques which involve the digitization of hundreds of fiber bundles throughout the volume of the muscle (Kim et al., 2007). This robust data-base would likely be valuable for creating a comprehensive musculoskeletal shoulder model with broad applications including shoulder biomechanics.

Fourth, the instruments used to measure FBL varied between the studies. A potential limitation of digital or precision calipers is that curvature of muscle fiber bundles is likely not accounted for. Kim et al. (2007) used computer digitization techniques, which involves summating small distances along the fiber bundle, thus accounting for fiber bundle curvature.

The mean FBL of anterior region found by Roh et al. (2000) was greater than what Kim et al. (2007) reported. This difference in FBL could be attributed to different methodologies and number of fiber bundles represented in this value. Roh et al. (2000) excised "multiple" muscle fibers from the muscle belly, although the location and numbers of fiber bundles excised were not specified. The value reported by Kim et al. (2007) is based on hundreds of digitized fiber bundles obtained throughout the muscle volume.

2.4.3 Pennation Angle

In skeletal muscles, the PA of fiber bundles within the muscle allows more contractile tissue to be present in a given anatomic cross section (Gans & Bock, 1965). The angle of pennation is defined as the angle between the fibers and muscle axis of force generation (Lieber & Fridén, 2001) or the acute angle between the line of action of the tendon and the line of action of the muscle fibers (Murray et al., 2000). Since the line of axis/line of action is difficult to locate visually, PA is often measured as a surface angle, which is the angle between a fiber bundle relative to its attachment to the bone, tendon or aponeurosis (Mathewson et al., 2014; Roh et al., 2000; Ward et al., 2006; Zuo et al., 2012). For the supraspinatus muscle, only one study (Kim et al., 2007) was found to compute PA as the angle between the fibers and line of action of muscle fibers. Surface PA may be adequate for obtaining a general idea of PA, but methods used by Kim et al. (2007) may be more beneficial for future computer and finite element modelling, where defining PA as the angle between the fiber bundle and the line of force is a standard method.

Values of PA can also be highly variable depending on the location of measurements. This is particularly the case in a complex muscle such as supraspinatus where the anterior region is pennated and the posterior region is more parallel in orientation. Despite this chance for variability, the location of PA measurements in most studies was not clearly defined, making comparison of results difficult. In addition to the location of measurements, instruments used to quantify PA varied between the studies compounding to the wide disparity in PA values in the literature.

Furthermore, it is difficult to draw comparisons between the studies that have examined and provided the values of PA relative to the anterior and/or posterior regions of the muscle because of different methodologies and specimen characteristics (Kim et al., 2007; Roh et al., 2000; Zuo et al., 2012). As mentioned earlier, Kim et al. (2007) further calculated the PAs of the superficial, middle and deep parts of the anterior and posterior regions. They found significant variation in PA between the different parts of the muscle suggesting the depth within the muscle from which PA is measured can impact PA.

2.4.4 Muscle Volume

Muscle volume (MV) is an important measure to estimate PCSA of a muscle. The wide range in values found in the studies may be attributed to different methods of measurement of MV. Although fluid displacement is a reproducible method to estimate muscle volume, it may overestimate the actual muscle volume because of its inclusion of the internal tendons (Lee et al., 2012). Few studies (Aluisio et al., 2003; Peterson & Rayan, 2011; Ward et al., 2006), calculated MV using muscle mass and previously published density values. The fixed density values used were not specific to the muscle being studied, which can lead to error in PCSA values. In addition, the mass of muscle is also subject to change due to fixation methods (Ward & Lieber, 2005). One study (Tingart et al., 2003) determined the MV using MRI by outlining supraspinatus muscle from the Y-shaped position (the most lateral sagittal oblique image where spine of scapula is in contact with the coracoids process) to the medial border of scapula and to the insertion of supraspinatus on the humerus laterally. They also found a strong correlation between MV measured by MRI and water displacement.

2.4.5 Physiological Cross Sectional Area

The PCSA is the total cross sectional areas of all muscle fibers within the muscle (Lieber & Fridén, 2001). In many studies (Aluisio et al., 2003; Herzberg et al., 1999; Itoi et al., 1995; Johnson et al., 1996; Keating et al., 1993; Langenderfer et al., 2006), PA was not included in the calculation of PCSA and was simply calculated by dividing muscle volume by FBL or optimal FBL. This method can be used for muscles in which fiber bundles are oriented parallel to line of action where the PA is zero and most of the force is projected onto the line of action. However, in the case of pennated muscles such as supraspinatus, only a component of the force is projected onto the line of action. Therefore, PA is an important parameter that should be included in calculating the PCSA. Furthermore, the reported PCSA for the supraspinatus was quite variable which could be attributed to differences in the methods used to calculate MV and location of FBL sampling. In one study (Veeger et al., 1991), PCSA was calculated by digitizing the “thin coupes” removed from the muscle at the level of largest cross sectional area. However, it is not clear from the description of methods exactly how the measurements were made. Furthermore, the thin coupes taken from one part of the muscle may not account for all the fibers in the muscle and represent the cross sectional area of the muscle.

While PCSA is an important measure of muscle strength, its accuracy is dependent on the accuracy of other parameters such as FBL, PA and MV. For most of the studies, PA and FBL values were obtained from the superficial surface of the muscle, which may under or overestimate the PCSA values depending on the orientation of the fibers. For example, the fibers in the superficial part of the anterior region of supraspinatus are less pennated compared to its deep part (Kim et al., 2007), as such PCSA may be overestimated if fiber bundles are sampled from superficial surface only. In a recent study (Ravichandiran et al., 2010), significant differences between the PCSA of supraspinatus calculated using fiber bundles from superficial layer and entire volume of the muscle were noted. They also determined PCSA using a novel fiber bundle element model method where the data collected from digitized fiber bundles throughout the muscle volume were used and the computer algorithms accounted for variation in PA between the different parts of the muscle. Since this method does not rely on sarcomere length, FBL, and MV, it was suggested that this method is more precise than other methods.

2.4.5 Muscle Length

The length of a muscle is an important architectural feature as the ratio of normalized FBL to normalized ML indicates the muscle's excursion ability and allows comparisons between the muscles (Ward et al., 2006). Muscle length (with or without normalization) was measured in some studies (Langenderfer et al., 2006; Mathewson et al., 2014; Peterson & Rayan, 2011; Vahlensieck et al., 1994; Volk & Vangsness, 2001; Ward et al., 2006), but Ward et al. (2006) and Mathewson et al. (2014) were the only studies that provided a definition for ML. They defined it as "the distance from the origin of the most proximal fibers to the insertion of the most distal fibers in each tendon". For other studies, it was not possible to determine if the ML was the length of muscle or the combination of both muscle and tendon.

2.4.6 Quality Assessment

The quality assessment checklist was developed to assess the methodological quality and identify the critical elements in conducting architectural studies of human skeletal muscles. Moreover, the results of the quality assessment in addition to the results from the quantitative analysis strengthen the conclusions and recommendations of the reviews. The results of the assessment indicate the methodological quality of most of the studies is low. Heterogeneity among study methodologies and lack of description reduces the validity, reliability and potential of these studies to influence evidence based practice. In our view, high quality studies with sufficient uniformity of methods are needed to be truly useful for modelling purposes and guiding clinical decisions.

2.4.7 Strengths and Limitations of this systematic review

There are several strengths of this systematic review. First, a comprehensive search strategy was used to find the studies that investigated the architecture of normal supraspinatus. Second, we followed Prisma guidelines and Cochrane handbook for systematic reviews of intervention in this review. Third, we developed a highly reliable critical appraisal tool to assess the quality of selected studies. Fourth, despite of the small number of studies included in this review, we were able to make some comparisons and provide a detailed descriptive analysis.

One of the major limitations of this review was that we were not able to draw direct comparisons between the studies due to heterogeneity of methods and lack of information on the characteristics of cadaveric specimens. Due to the exclusion of 52 studies that were not in English, it is possible that we missed some high quality studies. Furthermore, we did not search any non-English databases which might have helped to identify additional studies. We did not contact the authors for any missing data and/or additional information which may have altered our quality assessment results.

2.4.8 Recommendations and Implications for Future Research

We adapted the EPICOT (evidence, population, intervention, comparison, outcomes and timestamp) approach (Brown et al., 2006) to describe implications and make recommendations for future studies.

- *Evidence*: Given the high variability in the methodologies used, we suggest that a clear and uniform measurement definition and method of architectural parameters need to be stated, so that accurate data that provides the most clinically relevant information can be established.
- *Population*: In order to better generalize the architectural findings of studies, we recommend that the age and gender of specimens should be clearly specified to assess their influence on the muscle architecture.
- *Study methods*: There were only a few studies of high methodological quality for the supraspinatus muscle architecture. The location and number of fiber bundles sampled should be carefully taken into consideration for precise measurements of FBL and PA. We also recommend that sarcomere length be measured for each specimen to normalize FBL.

- *Comparison*: Researchers should strive to generate accurate and robust data sets of normal supraspinatus architecture which could further be used to compare and gain understanding of the architecture of pathological supraspinatus.
- *Outcomes*: In the past, architectural features of the supraspinatus have been studied as though the muscle belly was made up of one uniform region. However, recent studies have demonstrated two distinct regions of the muscle. Therefore, the investigators need to be more explicit in exploring and presenting the architectural data throughout the volume of muscles.
- *Timestamp*: The review should be updated in three to five years of time.

2.5 Conclusion

Based on this systematic literature review, it is evident that there is a wide disparity of reported architectural values for the supraspinatus. Despite the clinical importance of supraspinatus and the integral role architectural data plays in elucidating joint biomechanics, only a few studies were found to provide the level of detail and quality suitable for advancing our understanding of shoulder biomechanics and developing accurate musculoskeletal models. Furthermore, with several methodological limitations and lack of clear descriptions, it is difficult to replicate the methods and generate confidence in the reliability of the majority of studies. Although these studies provide some information on the architectural features of the supraspinatus, for most, the clinical use of reported data is limited. The critical factors identified and specific recommendations made in this paper will guide researchers to determine the quality of architectural data obtained from cadaveric studies and its usefulness to progress clinical applications and develop sophisticated muscle models that will better replicate the behaviour of the musculoskeletal system.

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Appendices

Table of Appendices

Appendix 1

Medline (OVID) Search Strategy

1. morpholog*.mp.
2. architectur*.mp.
3. structur*.mp.
4. ((fascicle or fiber or fibre or muscle or sarcomere) adj2 length).mp.
5. pennation angle.mp.
6. (muscle adj2 (thickness or length or volume or mass or parameters or size)).mp.
7. cross sectional area.mp.
8. 1 or 2 or 3 or 4 or 5 or 6 or 7
9. Shoulder/
10. shoulder.mp.
11. supraspinatus.mp.
12. Rotator Cuff/
13. rotator cuff.mp.
14. Shoulder Joint/
15. glenohumeral.mp.
16. upper arm.mp.
17. 9 or 10 or 11 or 12 or 13 or 14 or 15 or 16
18. Cadaver/
19. cadaver*.mp.
20. specimen*.mp.
21. 18 or 19 or 20
22. 8 and 17 and 21

Appendix 2

Screening Selection Criteria

Level I

<u>Based on the title of the report</u>

1. Muscle architectur*/parameter*/morphology*/geometr* (including terms fiber/fibre length, fascicle length, fiber/fibre bundle length, muscle fascicles/fiber,/fibre, pennation angle, physiological cross sectional area, cross sectional area, muscle length), muscle volume/size? **Yes or uncertain- include and go to level 2**

OR

2. Muscles (supraspinatus/rotator cuff), muscle function (rotation/abduction), body part (shoulder/glenohumeral/upper arm/upper limb/upper extremity)? **Yes or uncertain- include and go to level 2**

OR

3. Cadaver* / Cadaver* anatom*? **Yes or uncertain - go to level 2**

OR

4. English Language? **Yes or uncertain- include and go to level 2, No- exclude**

For the study to pass to level 2, at least statement 1 or 2 must be selected and have a total of 2/4

Level II

<u>Based on the abstract of the report</u>

1. Cadaver* / Cadaver* anatom*? **Yes or uncertain- include and go to level 3, No- exclude**

OR

2. Muscle architectur*/parameter*/morphology*/geometr* (including terms fiber/fibre length, fascicle length, fiber/fibre bundle length, muscle fascicles/fiber,/fibre, pennation angle, physiological cross sectional area, cross sectional area, muscle length), muscle volume/size? **Yes or uncertain- go to level 3, No-exclude**

AND

3. Muscles (supraspinatus/rotator cuff), muscle function (rotation/abduction), body part (shoulder/glenohumeral/upper arm/upper limb/upper extremity)? **Yes or uncertain- include and go to level 3, No- exclude**

AND

4. Study deals with human cadaveric specimens? **Yes or uncertain- go to level 3, No-exclude**

AND

5. Five or more than five specimens included in the study? **Yes or uncertain- include, No- exclude**

AND

6. English Language? **Yes or uncertain- include and go to level 3, No- exclude**

AND

7. Full-text? **Yes or uncertain- include and go to level 3, No- exclude**

For the study to pass to level 3, at least statement 2, 3, 4, 5, 6 and 7 must be selected and have at least a total of 6/7

Level III

Based on the full-text of the report

1. Muscle architectur* (including terms fiber bundle length, pennation angle, physiological cross sectional area, cross sectional area, muscle length), muscle volume/size? **Yes-include, No- exclude**

AND

2. Study deals with normal supraspinatus? **Yes – include, No- exclude**

AND

3. Study deals with human cadaveric specimens? **Yes- include, No- excludes**

AND

4. Five or more than five specimens included in the study? **Yes- include, No-exclude**

For the study to be included in the review, a total of 4/4 statements MUST be answered ‘Yes’

Any uncertainty will be resolved by discussion.

Transition

In the second chapter, previous studies on the architecture of normal supraspinatus were systematically reviewed and assessed for their quality. Based on this extensive review, several methodological limitations of the previous architectural studies were found which limits the clinical use of the reported data. Several important factors which could potentially influence the muscle architectural data were highlighted and discussed in this review. The recommendations provided will assist researchers in advancing future muscle architectural studies and generate more accurate data sets. Establishing an accurate and comprehensive understanding of the normal architecture of skeletal muscles is essential to then understand the architectural changes that occur following surgical repair (Chapter 3) and in response to strength training (Chapter 4).

CHAPTER THREE

SURGICAL REPAIR OF THE SUPRASPINATUS: ARCHITECTURAL CHANGES IN THE MUSCLE PRE- AND POST-OPERATIVELY

3 Manuscript #2

Title: Surgical repair of the supraspinatus: architectural changes in the muscle pre- and post-operatively.

Introduction: Surgical repair of the supraspinatus with rotator cuff tears is common. The structural failure rate of these repairs can exceed 50%. Shortening of the tendon and muscle are recognized as strong predictors for repair failure. Despite its clinical significance, in vivo changes of the muscle architecture within the supraspinatus following surgical repair have not been thoroughly investigated. To improve rehabilitative and surgical management and optimize function of the repaired muscle, knowledge of the architectural changes following repair is critical. Thus, the purpose of this study was to compare the architectural features of the supraspinatus pre- and post-operatively at different time intervals.

Methods: Participants with full thickness supraspinatus tendon tears were recruited. A previously developed ultrasound protocol was used to image the supraspinatus pre-operatively (pre-op) and post-operatively at 1 (post-op1), 3 (post-op2) and 6 (post-op3) months. Architectural parameters quantified included fiber bundle length (FBL), pennation angle (PA), and muscle thickness (MT). Scans were performed in relaxed (0° glenohumeral abduction) and contracted (60° active glenohumeral abduction) states except at post-op1 where active muscle contraction was contraindicated. Self-reported function and maximal isometric shoulder abduction and external rotation strengths were assessed using the Western Ontario Rotator Cuff Questionnaire (WORC) and the hand-held dynamometer respectively.

Analysis: All statistical analysis was performed using SPSS. Pre- and post-operative architectural and strength data were compared using repeated measures ANOVA and paired t-tests. Statistical significance was set at $p<0.05$ with Bonferroni adjustments made where appropriate.

Results: Eight surgical candidates (7M/1F), mean age of 53.9 ± 4.8 years participated in this study. The WORC questionnaire and strength testing was completed only by five participants (4M/1F). Mean FBL increased significantly from pre-op to post-op1 ($p=0.001$) in the relaxed state and from pre-op to post-op2 ($p=0.002$) in the contracted state. A significant decrease in FBL was observed from post-op2 to post-op3 in the relaxed state. Mean PA significantly decreased from pre-op to post-op1 ($p<0.001$) in the relaxed state. However, a significant increase was observed from post-op2 to post-op3 in both relaxed ($p=0.006$) and contracted states ($p=0.004$). No significant differences for MT were observed at any time point in any state ($p>0.05$). For the WORC, an increase of 47.67% in the overall function was observed

from pre-op to post-op3. At post-op3, the external rotation (p=0.009) and abduction strength (p=0.005) were found to be significantly greater than post-op2.
Conclusions: The stretching of the supraspinatus during the surgery lengthens fiber bundles. Based on the observed length changes, reported sarcomere lengths and the cross bridging principles of skeletal muscles, the amount of lengthening from pre-op to post-op1 likely results in overstretching of the sarcomeres. This overstretching will affect the length-tension relationship of the muscle, which in turn can compromise its function and may lead to inferior surgical outcomes. Thus, exercise loads during rehabilitation should be kept low until at least 3-4 months following surgery to allow the muscle to adapt to its optimal FBL and prevent re-tears. The understanding of these architectural changes could guide clinicians to optimize loads, velocities and shoulder ranges for rehabilitation protocols.

3.1 Introduction

Rotator cuff tears involving the supraspinatus tendon are common and can be associated with debilitating pain and dysfunction in the shoulder (Reilly et al., 2006). The size and degree of supraspinatus tendon tears can range from low-grade partial thickness tears to massive full-thickness tears. In the general population, the prevalence of rotator cuff tears has been reported to be up to 22% (Minagawa et al., 2013). A partial thickness tear of the supraspinatus can progress and become a full-thickness tear and involve the other rotator cuff tendons if not detected and addressed early (Perry et al., 2009).

Supraspinatus tendon tears are associated with structural and architectural changes in the tendon and muscle (Kim et al., 2013). The importance of muscle architecture in elucidating the functional properties of the muscle and its role in clinical decision making has been documented in several studies (Gans, 1982; Lieber & Brown, 1992; Lieber & Fridén, 2001). Architectural parameters of the muscle such as fiber bundle length (FBL), pennation angle (PA), physiological cross-sectional area (PCSA) and muscle volume (MV) directly influence muscle excursion and its force producing capacity (Gans, 1982); they can predict the forces on the musculoskeletal system and provide a mechanical basis of muscle injury during various loading conditions (Delp & Zajac, 1992).

Changes in muscle architecture as a result of tendon injuries have been reported in numerous previous studies. Meyer et al. (2004) reported a shortening of fiber bundles and an increase in PA following tendon release of the infraspinatus in a sheep model. Similarly, Itoi et al. (1995) and Zuo et al. (2012) reported a shortening of FBL and an increase in PA in cadaveric specimens with full-thickness supraspinatus tendon tears with retraction respectively. In an in vivo study, Kim et al. (2013) examined the architectural changes distinctive of the anterior and posterior regions of the muscle in patients with full-thickness tendon tears. Compared to normal controls, shortening in FBL was greater in the posterior region compared to the anterior region. PA of the anterior region was found to be smaller in patients with full-thickness tear with retraction compared to normal controls.

The treatment of rotator cuff tendon injuries is multifaceted and varies from conservative physical therapy to surgical interventions such as arthroscopic debridement and reattachment of the torn tendon(s). Tears which do not respond to non-operative treatments are often surgically treated with pain relief and functional improvement being the primary goals. Despite the advances in surgical techniques, the incidence of re-tear and failure of surgical repair is high, ranging from 11.4 % (Lafosse et al., 2007) to 94% (Galatz et al., 2004). There has been a great deal of interest in the factors that contribute to the success of surgical repair of full-thickness tears including the extent of fatty infiltration, atrophy and size of the tear; however, little is known about the association of muscle morphology with the surgical repair and functional outcomes. A greater understanding of these architectural changes may allow for surgeons and rehabilitation specialists to be better informed on the functional consequences of surgical repair techniques. The amount of tension that can be applied to reattach the tendon during surgical repair and exercises to improve function without causing further trauma to the muscle can be decided.

To date, several investigators have studied the physiological changes in the supraspinatus muscle following full-thickness tendon tears and surgical repair such as the amount of fatty infiltration and atrophy. However, despite the clinical and functional relevance, muscle architectural changes in humans following surgical repair at different time intervals have not been investigated. Moreover, the implications of these architectural changes with respect to the functional outcome following surgical repair have yet to be assessed.

The morphology of supraspinatus has been investigated using cadaveric dissection (Itoi et al., 1995; Kim et al., 2007; Roh et al., 2000) and several imaging modalities including ultrasound (Kim et al., 2010) and magnetic resonance imaging (MRI) (Tingart et al., 2003). Ultrasound (US) is an ideal imaging technique in clinical and rehabilitative settings because it is portable, easily accessible, and non-invasive (Pillen & van Alfen, 2011). It is also an established method for quantifying FBL, PA, cross sectional area (CSA) and muscle thickness (MT) in both the normal and pathological supraspinatus muscle (Kim et al., 2013; Kim et al., 2010; Yi et al., 2012). Therefore, the main objectives of this prospective observational study were (1) to quantify and compare the fiber bundle architecture within the anterior region of the pathologic supraspinatus pre- and post-operatively at multiple time points using real-time ultrasound and, (2) to assess and discuss the possible functional implications.

3.2 Methodology

3.2.1 Participants & Study Design

Ethics approval was obtained from the Biomedical Research Ethics Board, University of Saskatchewan (BioREB # 11-53). Participants were recruited from a single orthopaedic surgeon's practice (Saskatoon, Saskatchewan). To be included, participants were required to have a full-thickness tear of the supraspinatus tendon confirmed with US or MRI, and be scheduled for arthroscopic surgical repair. Participants were excluded if they had any prior shoulder surgery, neuromuscular disease, and any other conditions that could limit the active shoulder abduction. Eligible participants were identified by the surgeon and with the participants' consent, were contacted by the study investigator via telephone. Participants' medical history was collected and screened once again for the study inclusion criteria. Each participant was provided with the study information sheet to carefully review and signed consent was obtained prior to the first testing session.

3.2.2 Ultrasound Imaging Protocol

Each participant attended four US scanning sessions: one pre-operatively and three post-operatively at different time intervals. The post-operative sessions were scheduled at one month (post-op1), three months (post-op2) and six months (post-op3) after the surgery. For each of the scanning sessions, the participants were seated with their back supported in a chair with adjustable height. A previously validated ultrasound protocol by Kim et al. (2010) was used to scan the muscle. In all testing sessions, scans were performed in two shoulder positions, with the exception of one month follow-up (post-op1) session where active muscle contraction was contraindicated. First, the muscle was scanned in a relaxed state (0° glenohumeral abduction) with the arm resting by the participant's side and the palm of hand at the side of the chair. Second, the muscle was scanned in the contracted state with the participants holding their arm against gravity at 60° abduction and neutral glenohumeral rotation position. A universal goniometer was used to measure the shoulder positions. To maintain consistency, all scans were performed by one researcher (RS) who was trained for the protocol by a researcher who is experienced in ultrasound scanning of supraspinatus. A portable ultrasound scanner (LOGIQ e BT08, GE Healthcare) fitted with a linear (38.4mm) 12 Hz transducer (resolution 0.3mm) was used. As outlined in previous studies (Kim et al., 2010; Kim et al., 2013; Kim et al., 2014) panoramic US images were taken to measure the fiber bundles of the anterior region of supraspinatus; the US probe was placed along the length of the muscle. To assess the thickness of the muscle, sagittal US images were captured by placing the probe perpendicular to muscle belly (Kim et al., 2010). In each arm position, 15-20 images (panoramic and sagittal) were captured. Measurement errors were minimized by keeping the tilt angle of US probe perpendicular to the fiber bundle plane and applying minimum pressure to ensure the underlying tissues were not deformed.

All data were saved on the US unit for subsequent analyses. The architectural parameters measured on the saved images were FBL, PA and MT. All the measurements were made by one investigator (RS) who received adequate training to perform measurements on the US images. Among the saved images, one image with the clearest fiber bundles in the middle part of the muscle belly was chosen. The middle part forms the majority of the anterior region (Kim et al., 2007). The fiber bundles in which medial and lateral attachment ends were apparent and that could be seen along the majority of its length were used. Length of the fiber bundles was computed as a linear distance between the medial and lateral attachment sites. Pennation angle was measured as the angle between the fiber bundle and its attachment to the intramuscular tendon (Figure 3.1). Thickness of the muscle was calculated using a previously published protocol by Yi et al. (2012) (Figure 3.2). Two lines were drawn on the skin, one along the scapular spine and another along the acromion. The point where two lines intersected was marked as acromion angle. Coracoid process was also marked and connected with the acromion angle. The scapular notch was identified with the US probe parallel to the muscle fibers. The probe was rotated and positioned parallel to the line connecting the coracoids process and acromion angle, with scapular notch placed at the center of the monitor. The acoustic shadowing of clavicle on one side and that of scapular spine on the other side were used as anterior and posterior borders respectively. The horizontal distance was measured between the two borders and the midpoint of this distance was marked. The vertical distance measured by drawing a line between the superior and inferior borders of the muscle passing through the midpoint provided the thickness of supraspinatus (Yi et al., 2012).

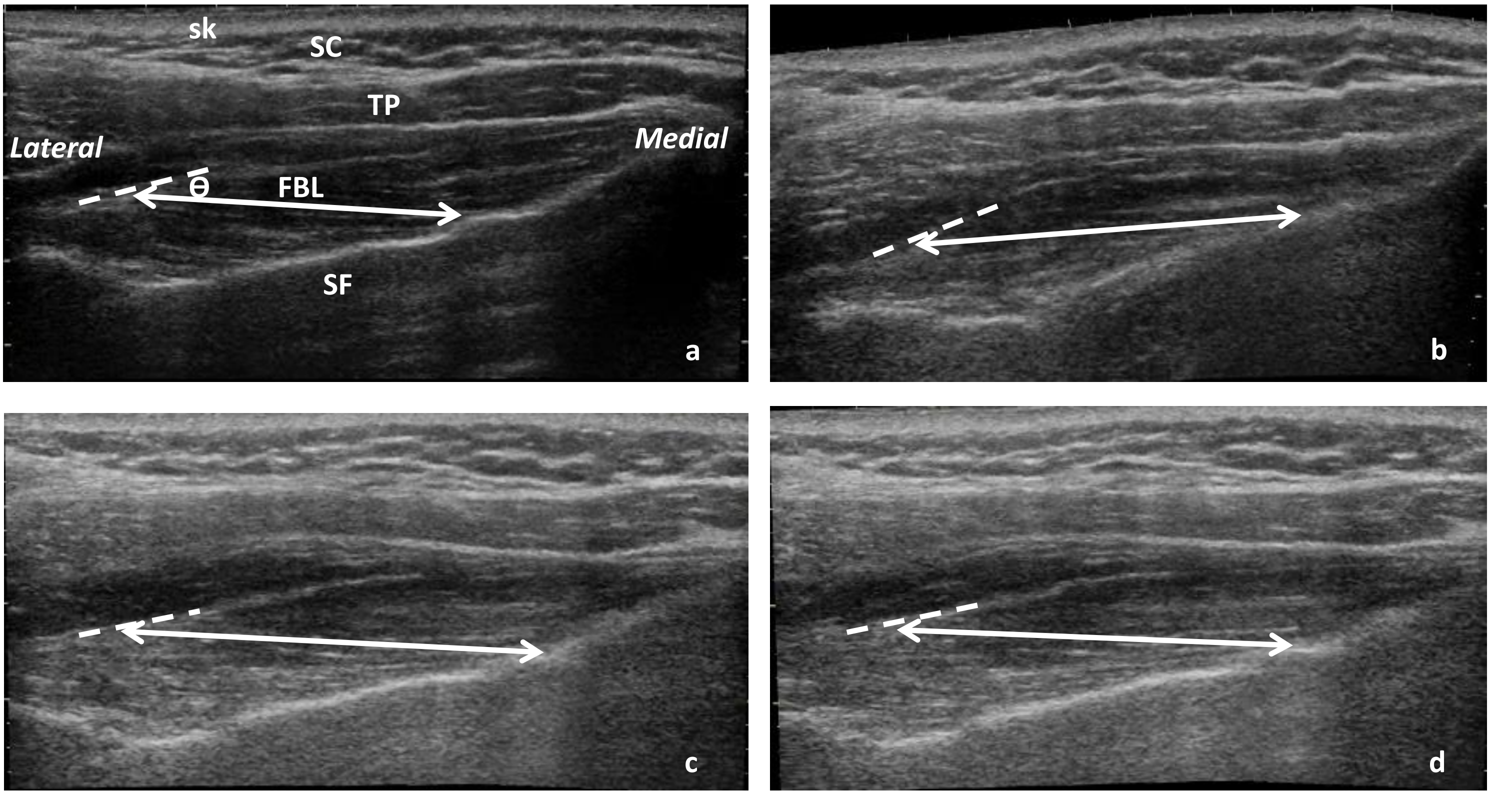


Figure 3.1 Panoramic US scan of right supraspinatus following injury and surgical repair in the relaxed state. **a**: pre-operative, **b**: post-op1, **c**: post-op2, **d**: post-op3. One fiber bundle from the anterior region is demarcated by a white line, Ɵ: pennation angle, FBL: fiber bundle length, sk: skin, SC: subcutaneous tissue, TP: trapezius muscle, SF: supraspinous fossa, **---** intramuscular tendon.

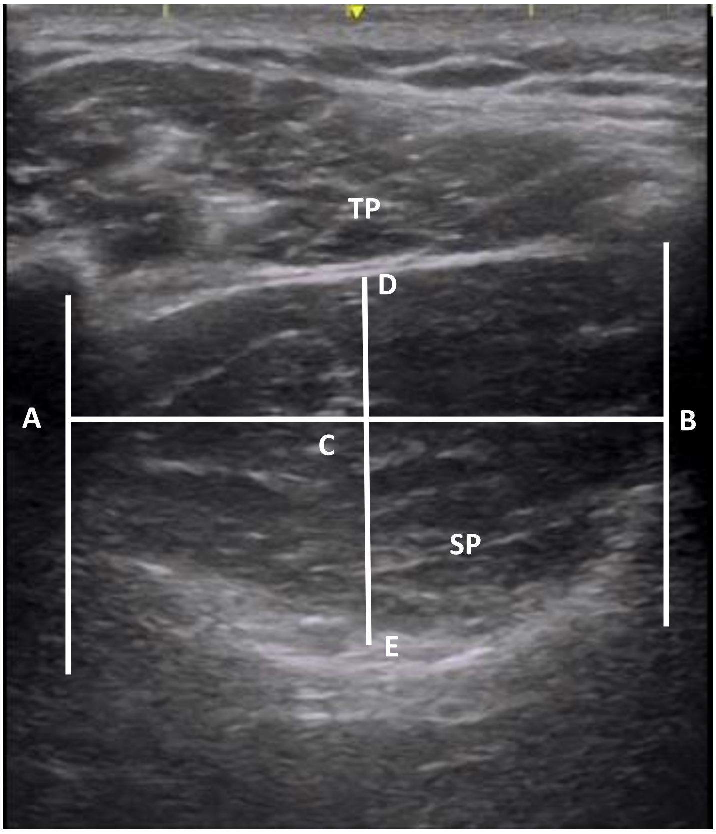


Figure 3.2 Sagittal US scan of right supraspinatus in the relaxed state. **TP**: trapezius, **SP**: supraspinatus, **A**: acoustic shadowing of clavicle, **B**: acoustic shadowing of scapular spine, **C**: mid-point of distance between A and B, **D**: upper border of supraspinatus muscle, **E**: lower border of supraspinatus muscle. Distance between D and E represents supraspinatus muscle thickness.

The strength testing was conducted after US scanning during each session except at post-op1 in which active abduction was contraindicated and the arm on which surgery was performed was still immobilized in an Ultrasling® or Smartsling® (abduction slings with a bolster). All participants were seated with their back supported and feet flat on the floor. Maximal isometric shoulder strength was assessed using a hand-held dynamometer (Lafayette Manual Muscle Test System, Lafayette Instrument, IN, USA). The hand-held dynamometer (HHD) was chosen because it is portable, easy to use and has been shown to be valid and reliable tool for strength testing (Bohannon, 1986; Magnus et al., 2014; Magnusson et al., 1990). Two shoulder positions were tested: abduction and external rotation. Each position was tested with the arm at 0° of shoulder abduction, 90° of elbow flexion and neutral supination/pronation position (palm facing medially) of the forearm. The padded stirrup of HHD was positioned perpendicular to the lower arm on the lateral side for shoulder abduction. For external rotation, the dynamometer was placed perpendicular and just above wrist proximal to the ulnar styloid process. The HHD was held stationary against the arm or forearm (depending on the position being tested) and participants received standard verbal encouragement to push into the HHD with maximum effort. For all the positions tested, participants were instructed to progressively increase their force and reach their maximum by the end of three seconds without flexing their elbow. The strength was measured twice in each position with 60 seconds rest between the two trials. The average value of two measurements was determined as the peak value (in kilograms). To maintain consistency, the dynamometer was placed at the same position during all the strength testing sessions and the same order of testing was followed for each participant (external rotation followed by abduction).

3.2.4 Western Ontario Rotator Cuff Questionnaire

To assess self-reported function, the Western Ontario Rotator Cuff Questionnaire (WORC) was used (see Appendix 1). The WORC has been shown to be a valid and reliable tool for assessing rotator cuff conditions and repairs (Kirkley et al., 2003). The 21-item questionnaire is organised into 5 domains: physical symptoms, sports and recreation, work, lifestyle and emotions. The WORC uses visual analog scale (VAS) for all questions and is scored by calculating the distance from the left side of the line to the point where the participants marked their response. Each item has a possible score range of 0-100 with a maximum score of 2100 after adding scores for all the domains. A higher score represents a more symptomatic shoulder and a lower quality of life. The total score can also be reported as a percentage of normal by subtracting the total from 2100, dividing by 2100, and then multiplying by 100. The total final WORC score can vary from 0% (dysfunctional shoulder) to 100% (the highest functional status level). The WORC questionnaire was assessed during each assessment session i.e. pre-operatively and post-operatively after 1, 3, and 6 months.

3.3 Data Analysis

All statistical analysis was performed using SPSS software (version 20; SPSS Inc., Chicago, IL, USA). Data were screened for normality, skewness and kurtosis before parametric tests were applied. Means and standard deviations were computed for each parameter (Tables 3.2-3.4). A repeated measures analysis of variance (ANOVA) was used to analyse the architectural parameters (FBL, PA and MT) and strength values and compare between pre and post-operative measurements. For architectural parameters, separate ANOVAs were conducted for relaxed and contracted states. Greenhouse-Geisser adjustment was applied when the assumption of sphericity was violated (Mauchly's test of sphericity, $p<0.05$). Paired student t-tests were used to compare differences in measured variables between two time points. Statistical significance was set at $p<0.05$ with Bonferroni adjustments made where appropriate ($p=0.05/4=0.013$; $p=0.05/3=0.017$). Percent change was used to analyze WORC scores. Percent score was calculated by subtracting the pre-training score from post-training score, dividing by pre-training score and multiplying by 100.

3.4 Results

Eight participants (7M/1F) aged 53.9 ± 4.8 (range 47-59) years participated in this study. Participants' demographics, tear sites and tear measurements are presented in Table 3.1. The architectural data for three of the eight participants was collected during the preliminary phase of the study where WORC questionnaire and strength training were not used as a part of the assessment. Therefore, the WORC questionnaire and strength testing was completed only by five participants (4M/1F). Two participants did not attend the post-op3 session for personal reasons and their data were excluded from the analysis.

Table 3.1 Participants' demographics, tear sites and dimensions

Participants	Age	Sex	Side	Rotator cuff tear location	Size of SP tear (ap x ml) (mm)
1	53	Female	Right	SP, SSC, BB	27 x 40
2	50	Male	Left	SP, ISP, SSC	27 x 42
3	56	Male	Right	SP, ISP	27 x 32
4	56	Male	Left	SP, BB	27 x 30
5	47	Male	Right	SP, ISP, SSC	27 x 42
6	59	Male	Left	SP, ISP	23 x 40
7	49	Male	Left	SP, ISP, BB	28.5 x 27.7
8	49	Male	Right	SP, SSC, BB	8 x 4.7

ap anterior-posterior dimension of the tear; **ml**: medial-lateral dimension of the tear. **SP** (supraspinatus muscle), **ISP** (infraspinatus muscle), **SSC** (supscapularis muscle), and **BB** (biceps brachii muscle).

3.4.1 Fiber bundle length

For FBL, there was a significant main effect of time in the both relaxed ($p<0.001$) and contracted ($p<0.001$) states. In the relaxed state, the mean FBL significantly increased from pre-op to post-op1 ($p=0.001$). A significant decrease in mean FBL was observed from post-op1 to post-op2 ($p=0.029$) which further decreased at post-op3 ($p=0.004$). Mean FBL at post-op3 was found to be significantly greater than the mean pre-op value ($p=0.014$).

When Bonferroni adjustments were made, mean FBL at post-op1 and post-op3 remained significantly different than pre-op ($p<0.013$) and post-op2 ($p<0.013$) respectively (Figure 3.3).

In the active state, mean FBL was significantly increased from pre-op to post-op2 ($p=0.002$). At post-op3, the mean FBL was significantly shorter compared to post-op2 ($p=0.025$). Similar to the relaxed state, mean FBL at post-op3 was significantly greater than pre-op value ($p=0.020$).

When Bonferroni adjusted, mean FBL at post-op2 was remained significantly different than pre-op ($p<0.017$) (Figure 3.3).

3.4.2 Pennation Angle

Similar to FBL, there was a significant main effect of time seen for PA in the both relaxed ($p=0.002$) and contracted ($p=0.023$) states. In the relaxed state, mean PA significantly decreased at post-op1 ($p<0.001$), but showed a significant increase at post-op3 from post-op2 ($p=0.006$). No significant differences for mean PA were found between pre-op and post-op3 ($p=0.21$). The results did not change after Bonferroni adjusting for multiple comparisons ($p<0.05/4=0.013$) (Figure 3.4).

In the active state, a significant increase was observed at post-op3 from post-op2 ($p=0.004$) (Bonferroni adjusted for multiple comparisons $p<0.05/3=0.017$) (Figure 3.4).

3.4.3 Muscle Thickness

No significant differences for MT were observed at any time point in any state ($p>0.05$) (Figure 3.5).

3.4.4 Western Ontario Rotator Cuff Questionnaire (WORC)

The subjective assessment of participants showed improvement over time. An increase of 47.67% in the overall function was observed from pre-op to post-op3.

3.4.5 Strength

For external rotation strength, there was a significant main effect of time ($p=0.002$). The mean external rotation strength at post-op3 was found to be significantly higher than pre-op ($p=0.011$) and post-op2 ($p=0.009$) (Figure 3.6).

There was a significant time main effect for the abduction strength ($p=0.015$). Similar to external rotation strength, the magnitude of abduction strength at post-op3 was shown to be significantly higher than pre-op ($p=.033$) and post-op2 ($p=0.005$) (Figure 3.7).

After Bonferroni adjusted for multiple comparisons for strength, no significant differences were detected for abduction strength between pre-op and post-op3 ($p>0.05/3=0.017$).

Table 3.2 Architectural parameters for supraspinatus pre- and post-surgical repair. All values are means (± SD)

Variable	State	pre-surgery	post-op1	post-op2	post-op3
Fiber Bundle Length (cm)	Relaxed	4.52 (0.68)	5.38 (0.73)*	5.15 (0.55)	4.96 (0.56)**
	Active	3.80 (0.62)	____	4.34 (0.40)[#]	4.32 (0.54)
Pennation Angle (˚)	Relaxed	18.13 (1.55)	15.40 (1.70)*	16.22 (4.34)	19.75 (3.81)**
	Active	21.99 (3.88)	____	20.53 (4.65)	23.95 (3.74)**
Muscle Thickness (cm)	Relaxed	2.62 (0.43)	2.71 (0.39)	2.78 (0.40)	2.60 (0.44)
	Active	2.83 (0.42)	____	2.98 (0.39)	2.79 (0.42)

* Significantly different than pre-surgery (adjusted for multiple comparisons, p<0.013). # 3 months and pre-surgery are significantly different (adjusted values) (p<0.017). ** 6 months significantly different than 3 months (adjusted for multiple comparisons, p<0.013).

Table 3.3 External rotation and abduction strength (kgs) pre- and post-surgical repair. All values are means (± SD)

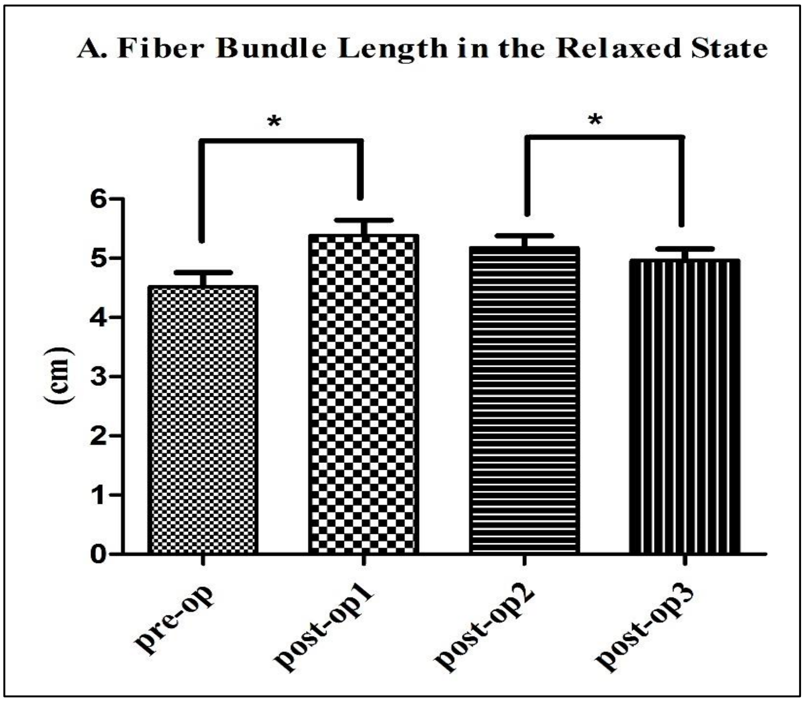
	pre-Surgery	post-op2	post-op3
External Rotation	3.58 (1.59)	4.78 (2.55)	5.86 (2.57)*
Abduction	16.52 (11.86)	19.94 (14.89)	22.77 (14.63)**

* Significantly different than pre-surgery and 3 months for external rotation (adjusted for multiple comparisons) ($p<0.017$). ** Significantly different than 3 months for abduction (adjusted values) ($p<0.017$).

Table 3.4 Western Ontario Rotator Cuff Questionnaire (WORC) (% function). All values are means (± SD)

	Pre-Surgery	post-op1	post-op2	post-op3
WORC	37.96 (19.21)	40.84 (14.98)	70.27 (19.07)	85.63 (12.34)

Note: Scores are a percentage of overall function (i.e. higher percentage indicates better function).



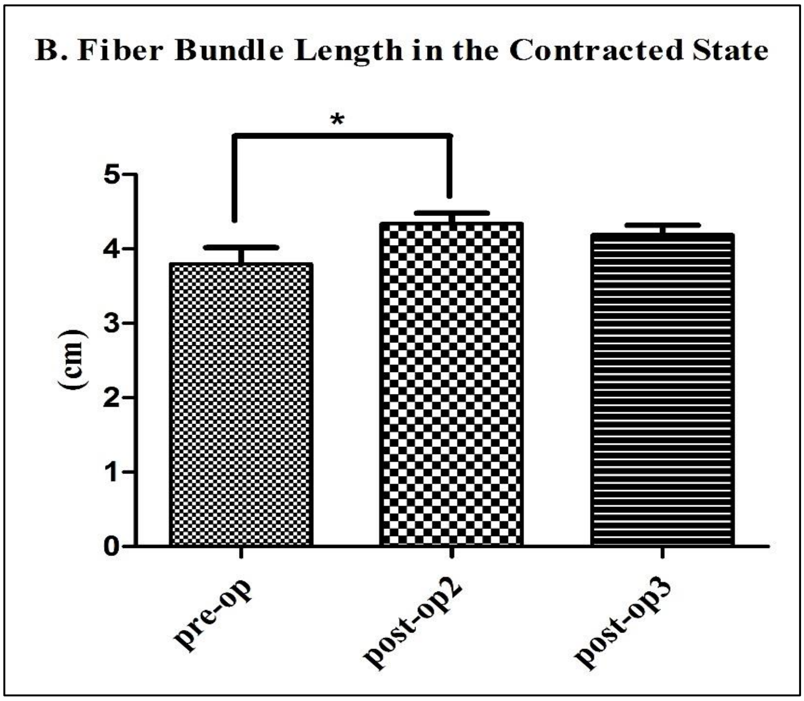
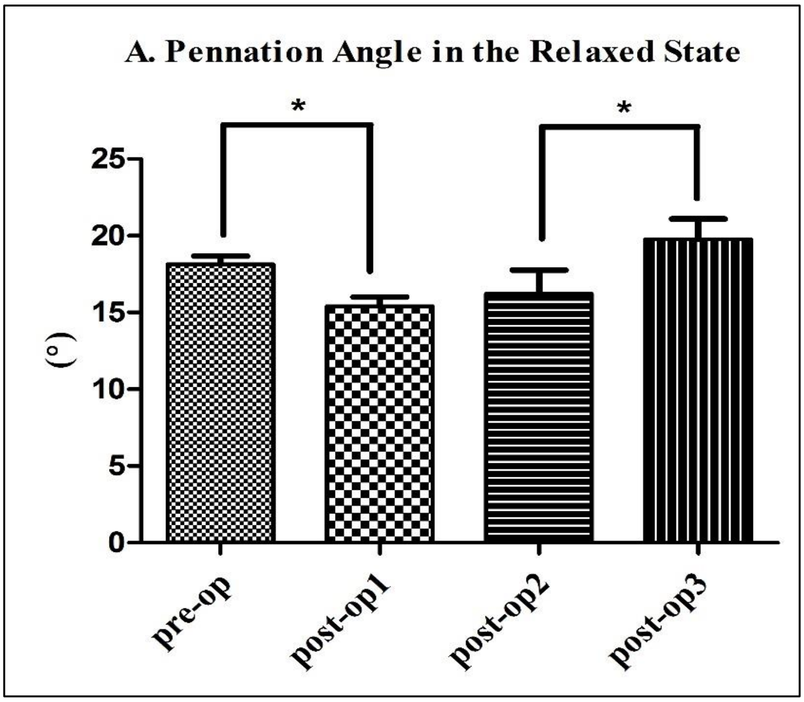


Figure 3.3 (A & B) Fiber Bundle Length changes pre- and post-operatively in the relaxed and contracted states. Values are means (±SE). There was a significant time main effect ($p<0.001$). ***** indicates significant differences (Bonferroni adjusted $p<0.013$, relaxed state; $p<0.017$, contracted state).



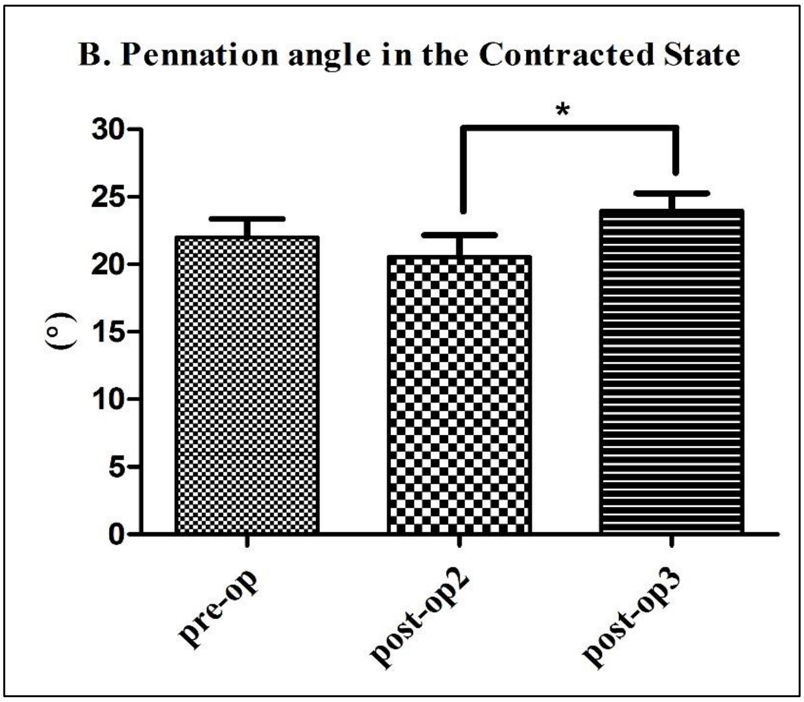


Figure 3.4 (A & B) Pennation Angle changes pre- and post-operatively in the relaxed and contracted states. Values are means (±SE). There was a significant time main effect ($p<0.001$). ***** indicates significant differences (Bonferroni adjusted $p<0.013$, relaxed state; $p<0.017$, contracted state).

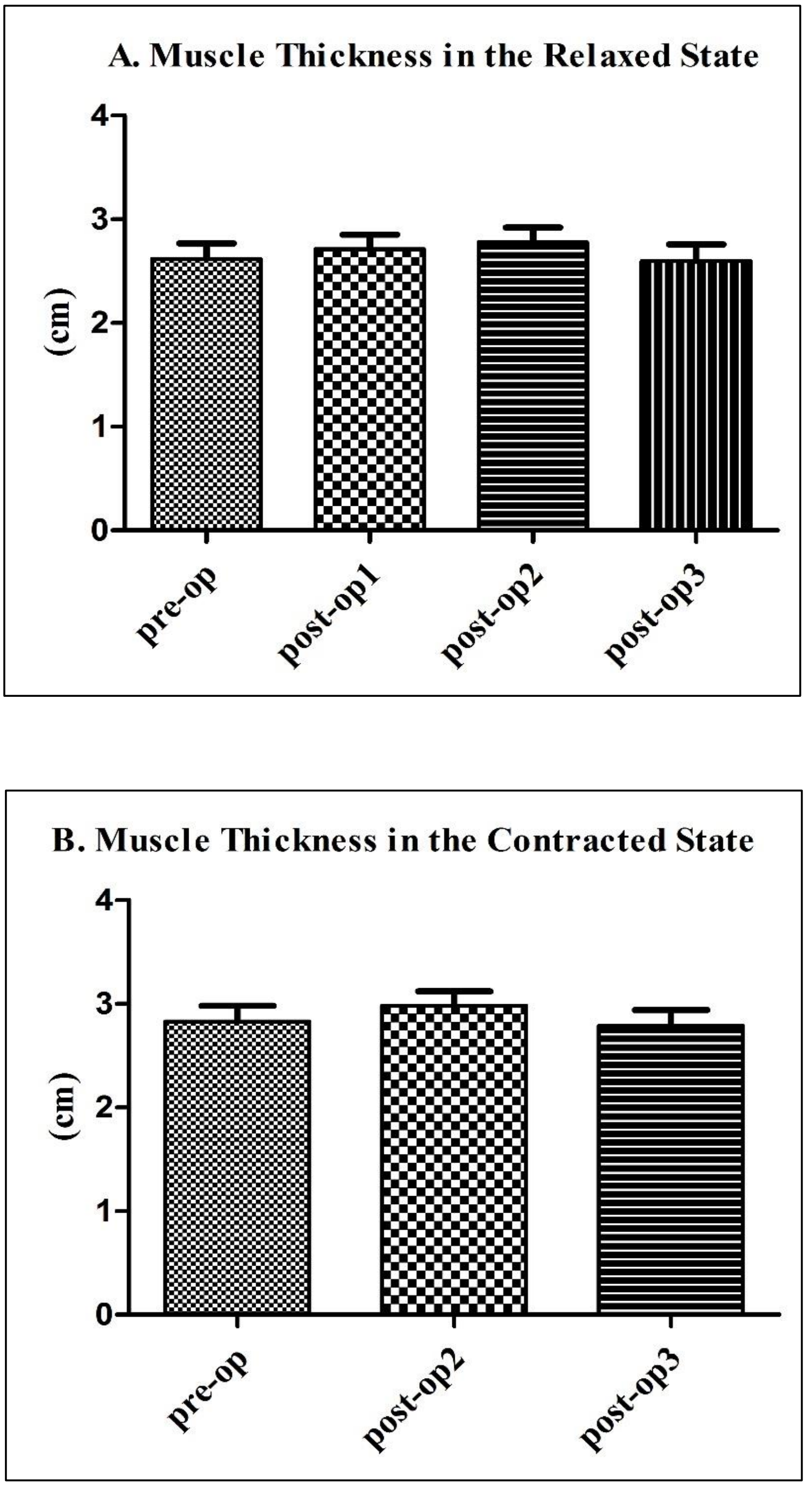


Figure 3.5 (A & B) Muscle Thickness changes pre- and post-operatively in the relaxed and contracted states. Values are means (±SE).

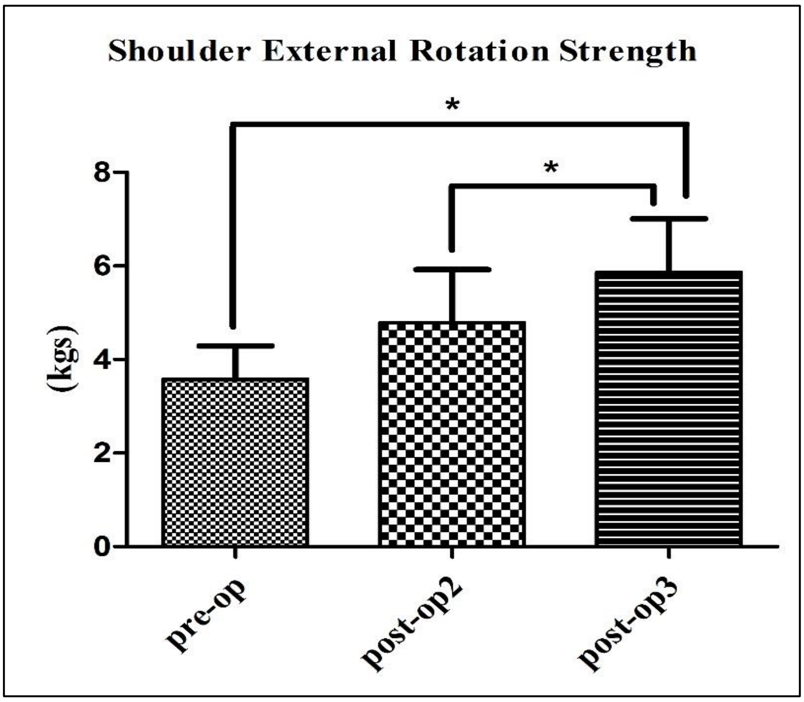


Figure 3.6 Shoulder External Rotation Strength changes pre- and post-operatively. Values are means (±SE). ***** indicates significant differences (Bonferroni adjusted p<0.017).

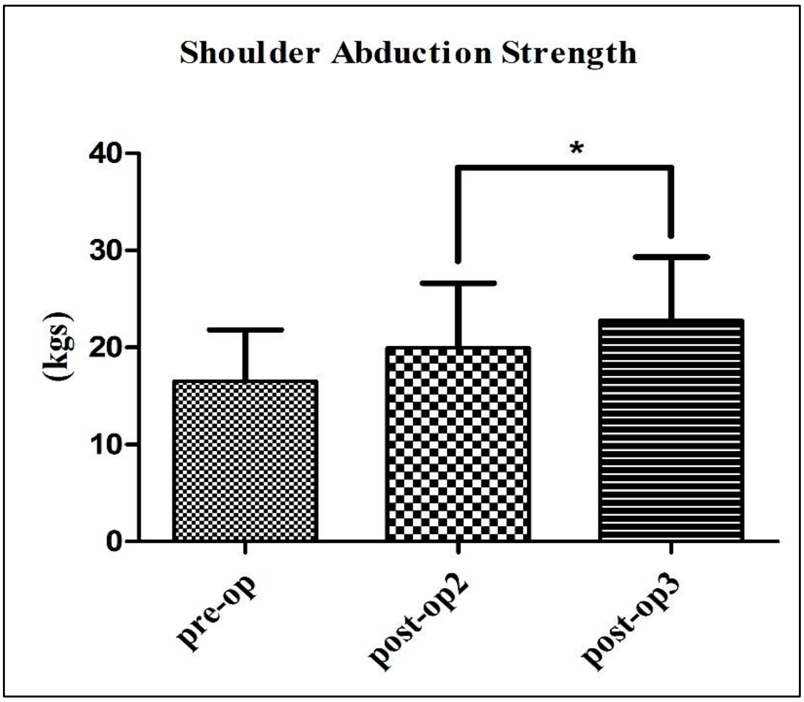


Figure 3.7 Shoulder Abduction Strength changes pre- and post-operatively. Values are means (±SE). ***** indicates significant differences (Bonferroni adjusted p<0.017).

3.5 Discussion

The primary objectives of this study were to quantify and compare the architecture of the supraspinatus muscle pre- and post-operatively to better understand these changes over the recovery period and to elucidate the impacts on muscle function and functional recovery of the shoulder. To our knowledge, this is the first study performed in humans to investigate changes in the supraspinatus architecture after rotator cuff repair. The findings of the study demonstrate significant differences in architectural parameters of the supraspinatus following surgical repair and these changes show a distinct pattern. The lengthening of fiber bundles was observed after one month of surgery which then decreased significantly by 6 months of surgery. In contrast, an initial decrease followed by an increase in PA overtime was found. The architectural data collected in this study have several clinical implications and may aid in improving the treatment of supraspinatus tendon tears. Additionally, the data available from this study can be used to develop biomechanical and finite element models that can simulate different surgical scenarios, predict functional outcomes and assist in planning post-operative rehabilitation protocols.

When a tendon is torn and the musculotendinous unit retracts, it is common to see fiber bundles within the muscle shorten (Kim et al., 2013; Tomioka et al., 2009). The shortening can continue to progress as long the tendon remains torn (Meyer et al., 2012). The mean FBL of supraspinatus in participants with retracted tears in our study was shorter than the mean FBL reported by Kim et al. (2013). The difference is likely attributed to the length in time since the initial tear and symptoms. The mean symptomatic period reported by our participants was 40 weeks whereas it was 24 weeks in the study by Kim et al. (2013). Thus, the tears were more chronic in nature for the participants in the present study.

As the torn tendon is re-attached to its footprint, the applied tension will result in stretching of the muscle and tendon, hence lengthening the fiber bundles. The tension applied onto the tendon during repair has been suggested to be an important factor for the repair outcome (Davidson & Rivenburgh, 2000) and force generating capacity of a muscle (Delp and Zajac, 1991).

To postulate the changes occurring at the sarcomere level following surgical repair of a torn supraspinatus tendon we considered the following example: The mean sarcomere length of the normal supraspinatus is 3.0 μm (Tomoika et al., 2009). Since the mean FBL of supraspinatus with an intact tendon is 5.60 cm (Kim et al., 2010), there would be approximately 18,666 sarcomeres (number of sarcomeres = length of fiber bundle/length of a sarcomere). The mean FBL of supraspinatus with a torn tendon found pre-operatively in our study was 4.52 cm which would correspond to approximately 15,066 sarcomeres. Following repair, the mean FBL at post-op1 lengthened to 5.38 cm. Assuming the muscle has not yet had a chance to adapt to the new length change, the number of sarcomeres pre-operatively remained consistent, and each sarcomere was stretched equally, the new length of each sarcomere at post-op1 would be approximately 3.6 µm. At a sarcomere length of approximately 3.6 µm, there is no overlap between actin and myosin (Hersche & Gerber, 1998; Rassier et al., 1999). The optimum fiber length for human fibers has been reported to be 2.7 µm (Walker & Schrodt, 1974). On a length tension curve, a change in the sarcomere length from 2.7 to 3.6 could result in a 30-40% decrease in force production capability of a muscle (Rassier et al., 1999). Thus, in theory, tension applied to the musculotendinous unit during surgical repair to re-attach the tendon will lengthen each sarcomere to an extent beyond their optimal length. This in turn will compromise the contractile force of the muscle due to the decrease in the myofilament (actin-myosin) overlap (Ward et al., 2010). To exacerbate this suboptimal state, in comparison to other rotator cuff muscles, the supraspinatus has been reported to be more sensitive to stretch because of its short fibers and long resting sarcomere lengths (Ward et al., 2006), so there are fewer sarcomeres for a given FBL.

Several animal studies have shown that skeletal muscles have the ability to adapt to lengthened or shortened positions by increasing or decreasing the number of sarcomeres respectively (Baker & Matsumoto, 1988; Simpson et al., 1995; Tamai et al., 1989). In addition to adapting to new lengths by adding or decreasing sarcomere number in series, these studies have shown skeletal muscles can maintain optimal sarcomere length and thus, its maximal force producing capability. However, this mechanism of sarcomere adaptation may only be applicable for particular muscles in animals. The results are not easily extrapolated to human muscles (Fridén & Lieber, 1998). This finding may be true for the highly adaptive soleus muscle of rodents, but is not necessarily true even for other muscles of the rodent hind limb (Spector et al., 1982). In addition, Fridén & Lieber (1998) found that in several tendon transfer cases in humans the adjusted sarcomere length following surgery was greater than the optimal sarcomere length.

In a cadaveric study which investigated the sarcomere length of rotator cuff muscles with intact tendons and those with full-thickness tendon tears, no significant differences between sarcomere lengths of supraspinatus with torn tendons from those with intact tendons were reported (Tomioka et al., 2009). With a chronic supraspinatus tendon tear, it may be possible that over time the number of sarcomeres decrease in order to regain their optimal length. However, whether this sarcomere adaptation occurs in human muscles following lengthening with surgical repair has yet to be investigated. Furthermore, it has been postulated that the sarcomere number-sensing mechanism may be disrupted or respond inappropriately with excessive stretch during surgical repair (Fridén et al., 2000).

There are different methods that have been suggested in the literature to avoid over tensioning during surgical repair. Continuous lengthening of the muscle-tendon unit has been suggested in previous animal studies to improve tendon-to-bone healing. This involves continuous progressive traction onto the tendon and muscle (Gerber et al., 2009). However, this is not a one-step surgical procedure. Use of reinforcement grafts and human dermal allografts have also been suggested to repair large and massive tears to enhance healing and restore muscle function (Agrawal, 2012). However, neither method is used regularly and are technically more challenging.

Although tendon properties were not investigated in this study, it is important to consider the changes in mechanical and structural properties of the tendon that occur with time from injury to repair. The amount of tension applied to the tendon is dependent on the elasticity of the tendon during surgical repair. In a muscle with short FBL such as supraspinatus, the force producing capability of the muscle is sensitive to changes in the tendon length (Delp and Zajac, 1991). In a rat shoulder model, Gimbel et al. (2004a) reported an initial decrease in tendon stiffness after tendon detachment followed by a progressive increase with time. Furthermore, in another study using the same animal model, Gimbel et al. (2004b) demonstrated a rapid increase in musculotendinous stiffness and repaired tension in the first few weeks after the tendon tear. Similar results, i.e. an increase in stiffness of musculotendinous unit, have been reported in chronic rotator cuff tears in humans (Davidson & Rivenburgh, 2000).

A significant reduction in FBL from post-op2 to post-op3 was observed in our study. This pattern of FBL reduction could be attributed to the specific adaptation patterns of the supraspinatus muscle and tendon to the surgical repair. In a recent animal study, Takahashi et al. (2010) found an asynchronous pattern between the muscle and tendon in response to a chronic length increase in the extensor digitorum of the second toe. They found an initial rapid increase in the number of sarcomeres in response to the stretch. This increase in sarcomeres was then reversed following the delayed adaptive response of the tendon. It was thought that the muscle adapted to the tendon elongation by subtracting the number of sarcomeres. Hence, at the end of 8 weeks, there was no significant difference between the tendon and muscle length of the experimental and control groups (Takahashi et al., 2010). It is possible that this process of muscle and tendon adaptation takes longer than 8 weeks in the human supraspinatus. Factors such as the nature of injury (acute vs chronic), muscle investigated (extensor digitorum vs supraspinatus) and subjects studied (animals vs humans) could influence the length of time needed for both the muscle and tendon to adapt. Recently, Meyer et al. (2012) found a dramatic increase in tendon length (8 mm) post-operatively in patients with full-thickness tears using MRI taken at an average of 24 months (range 6-50 months) after surgery. They hypothesized that this ‘pseudo’ lengthening of tendon could be due to unpacking of the central tendon due to degeneration and subsequent absorption of atrophied and retracted muscle fibers.

Post-operative rehabilitation is another important factor in the structural and functional recovery of the musculotendinous unit and may explain the significant reduction in FBL observed from post-op2 to post-op3. The muscular toning stage, generally starting at 3 months after the repair and may last up to 6 months depending upon the recovery of the patient, involves strengthening exercises, facilitation of functional movements to a near normal range and work and sports specific activities (Conti et al., 2009). These rehabilitation exercises may stimulate the muscle to adjust and adapt to its length which allow the muscle to optimally contract.

Finally, another reason why a significant reduction in FBL was seen could be due to a re-tear. As mentioned earlier, the re-tear rate following rotator cuff repair is very high. Thus, the reduction in FBL seen at post-op3 could be a result of surgical failure. Further study is needed to confirm these hypotheses.

Pre-operative PA measurements in full-thickness tears at rest (18.13±1.55°) found in this study are comparable to those reported by Thompson et al. (2011) (17.6±8.6°) and Zuo et al. (2012) (18.6±10°) using MRI and imaging software respectively. In contrast to FBL, a decrease in PA was found at post-op1 likely as a result of stretching of fibers in the plane of the muscle fibers. The fiber bundle changes observed in this study at post-op1 are consistent with a previous animal study (Elsalanty et al., 2007) and are reflective of lengthening of the muscle.

A significant increase in PA over time observed in the present study may be explained by the adaptation and reduced tension on the muscle fibers and the hypertrophy induced by the post-operative rehabilitation. Despite the shortening of muscle fibers and significant increase in PA, no significant changes in MT were seen at any time point. A possible explanation for this is that the muscle was inflamed initially due to tension applied to stretch the muscle and microtrauma induced by re-attaching the tendon to its insertion. At postop2, there was still no change seen in MT. Inflammation at 12 weeks post-surgery would likely have subsided, so the lack of change could be explained by new muscle fiber growth accounting for the space formerly occupied by inflammation. These changes cannot be easily differentiated using US imaging. Although we did not observe significant changes in MT at post-op3, a trend towards an increase in MT was found likely a result of post-operative rehabilitation.

For the WORC questionnaire, the decrease in composite score with time indicates improvement in perceived function after surgery. In order to assess a true clinically meaningful change in function from one time point to the other, a minimum change of 245 points in the WORC has been suggested (Kirkley et al., 2003). In our study, we observed a drop in composite score of more than 245 points from pre-surgery to post-op2 and post-op3. There was a change of 1001 points (an increase of 47.67% in the overall function) from pre-surgery to 6 months post-surgery. Our findings of improvements in patient reported outcomes following surgery are in agreement with the previous studies (Bey et al., 2011; Bigoni et al., 2009; Klintberg et al., 2009).

Recovery of strength was also noted over time. Previous research has shown most gains in strength and function are within the first year following surgical repair (Goutallier et al., 2009; Rokito et al., 1996). Similar to our study, Rokito et al. (1996) demonstrated the greatest improvement in strength during the first 6 months after surgery. Despite improvement of the repaired shoulder in strength during the early post-operative period, strength deficits relative to the contralateral shoulder have also been noted even after 24 months of the surgery (Bey et al., 2011). Various factors could attribute to these strength deficits including chronicity of tear, muscle quality, repaired tension, type and patients' adherence to rehabilitative protocols.

Rehabilitation following surgical repair of rotator cuff injuries is crucial for regaining strength and functional use of the shoulder. As previously discussed, lengthening of the muscle fibers during repair places the sarcomeres at non-optimal lengths, thus negatively impacting the muscle's force generating capacity. For the first 4 to 6 weeks following repair, avoiding aggressive range of motion exercises of the shoulder that could potentially further stress the already over lengthened muscle and the integrity of repair should be avoided. Assuming the sarcomeres have not attained their optimal length by 3 months, the exercise loads have to be kept low to prevent any disruption of sarcomere neogenesis or re-tear.

It has been shown in the literature that varying the type of exercise can influence sarcomere number. Lynn & Morgan (1994) found significantly more sarcomeres arranged in series in the vastus intermedius fibers of the rats in the downhill training group compared to those in the uphill training group. In a muscle that is sensitive to length changes such as supraspinatus (Ward et al., 2006), exercises that promote more sarcomeres to be arranged in series could be beneficial and allow the muscle to be active and produce forces over a greater range of motion. A recent study by Kim et al. (2014) investigated the effects of concentric and eccentric strength training on supraspinatus fiber bundle architecture and found that concentric loading led to significant shortening of FBL and eccentric loading to maintenance of FBL. Although this study involved only normal healthy population, the results suggest that gentle eccentric movements using low loads may be beneficial in a symptomatic population. By 6 months following repair, the FBL was significantly shorter suggesting adaptation of sarcomere number and length have occurred. The changes in muscle architecture, improvements in subjective self-reported outcomes and shoulder strength found in this study indicate the muscle has the capacity to contract and greater loads can be lifted by 6 months following surgery. Furthermore, during this phase (3 to 6 months) of recovery, the tendon to bone healing is strong enough to tolerate forces generated during strengthening. The strengthening load should be gradually increased at the beginning and progress to an advanced training by the end of 6 months. Overhead strengthening or lifting should be avoided to keep the stress below the mechanical strength of repair construct. Future studies should use this architectural data and simulate what types of loads and ranges are appropriate.

3.5.1 Limitations of the study

There were several limitations in our study. First, sample size was small. Small samples undermine the statistical power; however, despite this limitation, significant differences in the fiber bundle architecture were found in this study. Second, we did not assess the sarcomere length of supraspinatus. Quantification of sarcomere length changes with the stretching of tendon during surgical repair may have provided better understanding on the functional recovery of the muscle and the amount of tension that can be applied without damaging the sarcomeres. Third, we investigated the anterior region of the muscle which produces most of the force; however, the architecture of the posterior region of the supraspinatus also needs to be investigated as it has been shown to be significantly affected by the tendon injury (Kim et al., 2013).

3.6 Conclusion

Repair of the supraspinatus tendon during surgery lengthens fiber bundles of the muscle. The amount of lengthening from pre-op to 1 month after the surgical repair likely results in overstretching of the sarcomeres, affecting the length-tension relationship of the muscle. This in turn can compromise its function and may be associated with the prevalence of surgical failure. Exercise loads should be kept low during rehabilitation until at least 3-4 months following surgery to allow the muscle to adapt to its optimal FBL and prevent re-tears. By understanding these architectural changes following repair, different surgical and rehabilitation protocols can be tested and improved to facilitate the healing process and maximize functional recovery of supraspinatus.

3.7 Significance

The findings of the study provide an insight into the fiber bundle changes in the pathological supraspinatus following surgical repair and how the repair has influenced the muscle architecture and thus its function. The architectural data provided by this study could be used to develop better rehabilitation protocols and muscle models that can account for fiber bundle changes and predict the outcomes of surgical repair.

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Appendices

Table of Appendices

Appendix 1

Western Ontario Rotator Cuff (WORC) Questionnaire

WESTERN ONTARIO

ROTATOR CUFF INDEX

(WORC)©

A disease-specific quality of life measurement tool for patients with rotator cuff disease

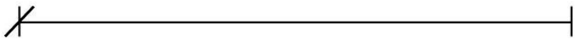
Suggested citation: The Development and Evaluation of a Disease-Specific Quality of Life Measurement Tool for Rotator Cuff Disease: The Western Ontario Rotator Cuff Index , American Academy of Orthopaedic Surgeon's Annual Meeting Book of Abstracts, 1998.

INSTRUCTIONS TO PATIENTS

In the following questionnaire you will be asked to answer questions in the following format and you should give your answer by putting a slash "/ " on the horizontal line.

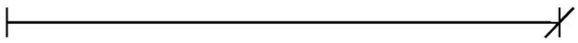
NOTE:

1. If you put a slash "/ " at the left end of the line i.e.



then you are indicating that you have no pain.

2. If your put your slash "/ " at the right end of the line i.e.



then you are indicating that your pain is extreme.

3. Please note:
a) that the further to the right you put your slash "/ ", the **more** you experience that symptom.

b) that the further to the left you put your slash "/ " , the **less** you experience that symptom.

c) please do not place your slash "/" outside the end markers

You are asked to indicate on this questionnaire, the amount of a symptom you have experienced in the past week as related to your problematic shoulder. If you are unsure about the shoulder that is involved or you have any other questions, please ask before filling out the questionnaire.

If for some reason you do not understand a question, please refer to the explanations that can be found at the end of the questionnaire. You can then place your slash "/ " on the horizontal line at the appropriate place. **If an item does not pertain to you or   you have not experienced it in the past week, please make your "best guess" as to which response would be the most accurate**

Section A: Physical Symptoms

INSTRUCTIONS TO PATIENTS

The following questions concern the physical symptoms you have experienced due to your shoulder problem. In all cases, please enter the amount of the symptom you have experienced in the last week. (Please mark your answers with a slash "/")

1. How much sharp pain do you experience in your shoulder?

no pain |————————————————| extreme pain

2. How much constant, nagging pain do you experience in your shoulder?

no pain |————————————————| extreme pain

3. How much weakness do you experience in your shoulder?

no weakness |————————————————| extreme weakness

4. How much stiffness or lack of range of motion do you experience in your shoulder?

no stiffness |————————————————| extreme stiffness

5. How much are you bothered by clicking, grinding or crunching in your shoulder?

none |————————————————| extreme

6. How much discomfort do you experience in the muscles of your neck because of your shoulder?

no discomfort |————————————————| extreme discomfort

SECTION B: Sports/Recreation
INSTRUCTIONS TO PATIENTS

The following section concerns how your shoulder problem has affected your sports or recreational activities in the past week. For each question, please mark your answers with a slash "/".)

7. How much has your shoulder affected your fitness level?

not affected |————————————————| extremely affected

8. How much difficulty do you experience doing push-ups or other strenuous shoulder exercises because of your shoulder?

no difficulty |————————————————| extreme difficulty

9. How much has your shoulder affected your ability to throw hard or far?

not affected |————————————————| extremely affected

10. How much difficulty do you have with someone or something coming in contact with your affected shoulder?

no fear |————————————————| extremely fearful

SECTION C: Work
INSTRUCTIONS TO PATIENTS

The following section concerns the amount that your shoulder problem has affected your work around or outside of the home. Please indicate the appropriate amount for the past week with a slash "/".

11. How much difficulty do you experience in daily activities about the house or yard?

no difficulty |——————————| extreme difficulty

12. How much difficulty do you experience working above your shoulder?

no difficulty |——————————| extreme difficulty

13. How much do you use your uninvolved arm to compensate for your injured one?

not at all |——————————| constant

14. How much difficulty do you experience lifting heavy objects at or below shoulder level?

no difficulty |——————————| extreme difficulty

SECTION D: Lifestyle
INSTRUCTIONS TO PATIENTS

The following section concerns the amount that your shoulder problem has affected or changed your lifestyle. Again , please indicate the appropriate amount for the past week with a slash "/".

15. How much difficulty do you have sleeping because of your shoulder?

no difficulty |————————————————| extreme difficulty

16. How much difficulty have you experienced with styling your hair because of your shoulder?

no difficulty |————————————————| extreme difficulty

17. How much difficulty do you have "roughhousing or horsing around" with family or friends?

no difficulty |————————————————| extreme difficulty

18. How much difficulty do you have dressing or undressing?

no difficulty |————————————————| extreme difficulty

SECTION E: Emotions

INSTRUCTIONS TO PATIENTS

The following questions relate to how you have felt in the past week with regard to your shoulder problem. Please indicate your answer with a slash "/".

19. How much frustration do you feel because of your shoulder?

no frustration |————————————————| extreme frustration

20. How "down in the dumps" or depressed do you feel because of your shoulder?

none |————————————————| extreme

21. How worried or concerned are you about the effect of your shoulder on your occupation?

not at all |————————————————| extremely concerned

THANK YOU FOR COMPLETING THE QUESTIONNAIRE

An Explanation of the Meaning of the Questions in the Western Ontario Rotator Cuff Index WORC

<u>Section A: Physical Symptoms</u>

Question 1.
Refers to pain in your shoulder that is quick and sudden or that you might refer to as a catching type of pain.

Question 2.
Refers to the dull background ache that always seems to be there as opposed to the sharp pain that is referred to in question 1.

Questions 3.
Refers to a lack of strength to carry out a movement.

Question 4.
Refers to the feeling of the joint not wanting to move. This is often experienced in the morning upon rising, after exercise or after a period of inactivity. It could also refer to not having full movement of your shoulder in all or any direction(s).

Question 5.
Refers to any of these sounds or feelings that you experience in your shoulder with any type of movement.

Question 6.
Refers to the amount of tension, pain or spasm that you experience in the muscles of your neck that seems to be caused by your shoulder problem.

<u>Section B: Sports/ Recreation</u>

Question 7.
Refers to the fitness level you maintained before your shoulder became a problem. Include a decrease in muscle tone or strength level, cardiovascular fitness or strength level.

Question 8
Refers to any overhead activity requiring you to use some force in its execution. If you do not throw a ball, please consider any other activity such as spiking in volleyball, throwing a stick to your dog, swimming the front crawl, serving in tennis, etc.

Question 9.
Please consider whenever you have been afraid or wary of someone or something hitting or coming into contact with your affected shoulder such as in a sport, a crowded room, an elevator or someone slapping your shoulder in a greeting .

Question 10.
Refers to any exercise requiring you to put force on your shoulder such as push-ups, bench press etc.

<u>Section C: Work</u>

Question 11.
This refers to activities such as raking, shoveling, vacuuming, dusting, weeding, hoeing and washing windows or floors etc.

Question 12.
Refers to any activity requiring you to raise your arms above shoulder level ie. putting dishes in a cupboard, reaching for an object, painting a ceiling or painting above shoulder level etc.

Explanation of Questions cont.

Question 13.
Refers to if you now use your other arm for any activity or work where you would ordinarily have done it with the arm on the problematic side. If your other shoulder is also symptomatic from Rotator Cuff Disease or some other disease, then consider how you would answer the question if that shoulder was normal.

Question 14.
This does not refer to lifting above your head but to lifting any heavy objects below shoulder level e.g. a bag of groceries, case of pop, suitcase, equipment at work, books, etc.

<u>Section D: Lifestyle</u>

Question 15.
Refers to having to change your sleeping position, waking up during the night, trouble getting to sleep or waking up feeling unrested.

Question 16.
Refers to anything that you would do to your hair such as combing, brushing or washing that requires you to reach up with your problematic arm.

Question 17.
Refers to any type of rough or vigorous play activity that you would normally engage in with your family or friends.

Question 18.
Refers to reaching behind to do up or undo a zipper or button(s), do up or undo a bra, pulling on or removing a sweater or top over your head, or tucking in a shirt or top.

<u>Section E: Emotions</u>

Question 19.
Refers to the frustration you feel because of your inability to do things you used to do or that you want to do but can't.

Question 20.
Down-in-the-dumps or depressed is self-explanatory

Question 21.
Refers to worrying about your shoulder getting worse instead of better or staying the same and being concerned about what effect that will have on your occupation or work (consider work inside or outside the home).

SCORING OF THE WESTERN ONTARIO ROTATOR CUFF (WORC) INDEX

1. Measure the distance from the left side of the line and calculate the score out of 100 (recorded to the nearest 0.5 mm.). Write it into the space provided for that question.
2. You can calculate a total score for each domain (Physical Symptoms/600; Sports and Recreation/400; Work/400 and Lifestyle/400;Emotions/400) or the total score for the domains can be summed for an aggregate score out of 2100.
3. Some find it more meaningful to report scores out of 100 i.e. a percentage of normal score. Since the worst possible score is 2100, the aggregate score is subtracted from 2100 and divided by 21. e.g. if your patient's total aggregate score = 1625; then the percentage score would be $\frac{2100 - 1625}{21} = 22.6\%$

The same applies for each domain.

physical symptoms

PS 1 ________.____

PS 2 ________.____

PS 3 ________.____

PS 4 ________.____

PS 5 ________.____

PS 6 ________.____

TOTAL

__________._____

sports/recreation

S 7 ________.____

S 8 ________.____

S 9 ________.____

S 10 ________.____

TOTAL

__________.____

work

W11________.____

W12________.____

W13________.____

W14 ________.____

TOTAL

_________._____

lifestyle

L 15 ________.____

L 16 ________.____

L 17 ________.____

L 18 ________.____

TOTAL

_______.____

emotions

E 19 ________.____

E 20 ________.____

E 21 ________.____

TOTAL _______.____

summary

PS ________.____

S ________.____

W ________.____

L ________.____

E ________.____

TOTAL:

__________._____

Transition

In chapter three, architectural parameters of the pathological supraspinatus were quantified and compared pre- and post-operatively at multiple time points to better understand the structural and functional recovery of the muscle. It was found that changes to architectural parameters i.e. FBL and PA of the muscle follow distinct patterns during the recovery period. Based on the findings, specific recommendations were made which may assist heath care professionals to design appropriate rehabilitation programs.

Rehabilitation plays a critical role in the success of the surgical repair of rotator cuff injury. Several exercises have been proposed in the literature to strengthen supraspinatus; however, the results regarding the best exercise to strengthen supraspinatus are still inconclusive. Thus, in light of the importance of the rehabilitation exercises, a research study was conducted to determine the optimal exercise for strengthening supraspinatus. Based on a review of the literature, there were three arm positions commonly used to strengthening the supraspinatus. Thus, for the last study of this thesis (Chapter 4) we investigated the architectural changes of the supraspinatus following strength training in these three arm positions.

CHAPTER FOUR

ARCHITECTURE CHANGES OF THE SUPRASPINATUS FOLLOWING EXERCISE TRAINING

4 Manuscript #3

Title: Architecture changes of the supraspinatus following exercise training

Introduction: Supraspinatus strengthening is an integral part of shoulder rehabilitation programs due to its involvement with a number of shoulder conditions. To date, there is a wide disparity regarding the best exercise to strengthen the supraspinatus. Understanding of fiber bundle changes with different exercises can assist clinicians in planning better shoulder rehabilitative protocols. Thus, the purpose of this study was to investigate the effects of different supraspinatus strengthening exercises on muscle fiber bundle architecture.

Methods: Participants were randomized into 3 exercise groups: full-can (FC), empty-can (EC) and prone horizontal abduction (PHA). Participants in each group performed 3 exercise sessions/week for 8 weeks. Each session involved 4 sets of exercise for weeks 1-4 and 6 sets for weeks 5-8 with 8 repetitions/set. A 30 seconds rest was provided in between each set. A previously validated ultrasound protocol was used to measure fiber bundle length (FBL), pennation angle (PA), and muscle thickness (MT) from saved images at the beginning, after 4 weeks and at the end of 8 weeks training program in 0° (relaxed state) and 60° active (contracted state) glenohumeral abduction. Maximum isometric shoulder abduction strength was measured using a hand-held dynamometer in three different positions: full-can, empty-can and prone horizontal abduction.

Analysis: Fiber bundle architectural and strength data were analysed using SPSS. Factorial ANOVA with repeated measures, one-way ANOVA and paired t-tests were used for comparisons. Bonferroni adjustments were made where applicable. Significance level was accepted at $p<0.05$.

Results: Thirty-four healthy participants (15M/19F), with mean age of 29.8 ± 7.3 years, volunteered to participate in the study. For FBL, there was a significant group X time interaction in the relaxed ($p=0.013$) and contracted ($p=0.023$) states with a main effect of time ($p<0.001$). Mean FBL decreased after 4 weeks of training in the FC (relaxed, $p=0.001$; contracted, $p=0.008$) and EC (relaxed, $p=0.008$; contracted, $p=0.013$), but it did not change in the PHA (relaxed, $p=0.12$; contracted, $p=0.49$). No changes in the mean FBL were observed from 4 to 8 weeks of training in any group. For PA and MT, no significant differences were shown between groups at any time point ($p>0.05$). There was a significant group X time interaction when the testing was performed in prone horizontal abduction position ($p=0.008$). A significant increase in strength was observed after 4 weeks in all the groups (FC, $p=0.005$; EC, $p=0.014$; and PHA, $p<0.001$), but it increased only in the PHA ($p=0.004$) after 8 weeks.

Conclusion: Findings of the study suggest that prone horizontal abduction may be a more suitable exercise to strengthen supraspinatus. However, the results should be interpreted with caution when dealing with symptomatic participants.

4.1 Introduction

Rotator cuff pathologies are prevalent in the general (Yamamoto et al., 2010) and athletic (Burkhart & Klein, 2004) populations, and can result in shoulder impairment, dysfunction and extensive periods of rehabilitation (Conti et al., 2009). The most commonly reported pathologies of the rotator cuff include subacromial impingement and rotator cuff tendinopathies which largely contribute to the occurrence of rotator cuff tears (Neer, 1983; NeerII, 1972). Of the four rotator cuff muscles, the supraspinatus is most susceptible to injury and commonly implicated with rotator cuff pathologies because of its vulnerable position between the acromion, humeral head and coracoacromial ligamentous complex (Cohen & Williams Jr, 1998). Loss of normal function of the supraspinatus may cause an imbalance of forces acting on the shoulder. This imbalance may lead to superior translation of the humeral head resulting from deltoid which may compress the subacromial tissues (Brossmann et al., 1996). Therefore, therapeutic exercises focussing on restoration of strength and optimal function of the supraspinatus are an integral part of shoulder rehabilitation programs.

Based on the supraspinatus muscle activation assessed with electromyography (EMG) and magnetic resonance imaging (MRI), researchers have proposed different exercises to strengthen the supraspinatus. The commonly suggested exercises include full-can (elevation of arm in the scapular plane with thumb pointing upwards), empty-can (elevation of arm in the scapular plane with thumb pointing downwards) and prone horizontal abduction. Jobes and Moynes (1982) advocated the use of empty-can to strengthen the supraspinatus based on increased muscle activity in this position. The empty-can was further supported by Townsend et al. (1991) who reported a peak value of 74% of the maximum voluntary isometric contraction in the supraspinatus with this shoulder positioning. However, other investigators have suggested prone horizontal abduction to be an optimal shoulder exercise to strengthen the supraspinatus based on the amount of activity produced (Blackburn et al., 1990; Worrell et al., 1992). Yet in some other EMG studies, no differences in the supraspinatus activity were found between these three exercises when performed isotonically (Reinold et al., 2007) or isometrically (Boettcher et al., 2009). Similarly, in a MRI evaluation study, Takeda et al. (2002) reported no significant differences in muscle proton spin-spin relaxation time (T2) of the supraspinatus between the full-can and empty-can exercises, indicating the same level of activity within the muscle in both the exercises. These results indicate there is still a discrepancy regarding the best exercise to strengthen the supraspinatus.

The primary criteria to select exercises to strengthen the supraspinatus in most recent studies were based on muscle activation levels detected with EMG (Boettcher et al., 2009;

Reinold et al., 2007), shoulder and scapular kinematics (Thigpen et al., 2006) or T2 relaxation time in MRI (Takeda et al., 2002). To our knowledge, there has been no study comparing the effectiveness of these exercises in relation to muscle architecture. Architectural parameters of skeletal muscles such as physiological cross-sectional area (PCSA), fiber bundle length (FBL) and pennation angle (PA) determine the functional properties of the muscle as they are closely associated with the contractile capability and excursion velocity of the muscle (Gans, 1982). Changes in these architectural parameters are well-known consequences of resistance training. Thus, a clear understanding of the muscle architecture and the changes associated with strength training can have significant clinical implications in rehabilitation of the shoulder.

Numerous studies have demonstrated the changes in muscle architecture of the upper and lower extremity muscles following exercise training (Aagaard et al., 2001; Blazevich et al., 2007; Kim et al., 2014). Since the precise calculation of PCSA is not always possible, many resistance training studies have calculated muscle thickness (MT) or cross sectional area (CSA) of the muscle to evaluate the contractile capability of the muscle (Farthing & Chilibeck, 2003; Farthing et al., 2009; Kim et al., 2014; Matta et al., 2011). The parameters most commonly reported to show changes after strength training include FBL, PA, MT and CSA. Kim et al. (2014) reported significant changes in FBL, PA and MT of the supraspinatus following concentric or eccentric strength training. Matta et al. (2011) found significant differences in MT at different sites in the biceps and triceps brachii muscles after 12 weeks of strength training in 40 healthy male subjects. In another strength training study, Aagaard et al. (2001) reported significant increase in pennation angle and anatomical cross-sectional area of vastus lateralis muscle following a period of 14 weeks of heavy resistance training.

To date, several imaging techniques have been employed to investigate morphological changes in muscle after resistance training such as ultrasound and MRI. Ultrasound (US) is a non-invasive, low-cost imaging modality and has been widely used to quantify changes in the muscle following strength training (Blazevich et al., 2003; Kim et al., 2014; Potier et al., 2009). The validity and reliability of ultrasound imaging to capture the muscle architecture of the supraspinatus has also been published previously (Kim et al., 2010). Moreover, its portability, accessibility and relative ease of performing repeated examinations make it an ideal choice for research and diagnostic purposes.

The purpose of the study was to examine and compare the effect of strength training using three different commonly prescribed concentric exercises on the fiber bundle architecture of the anterior region of supraspinatus using real-time ultrasound. We hypothesized that changes in the fiber bundle architecture of supraspinatus will be specific to the exercise being performed. The results of this study may allow clinicians to select optimal exercise to strengthen supraspinatus and aid in improving rehabilitative protocols for people with shoulder injuries.

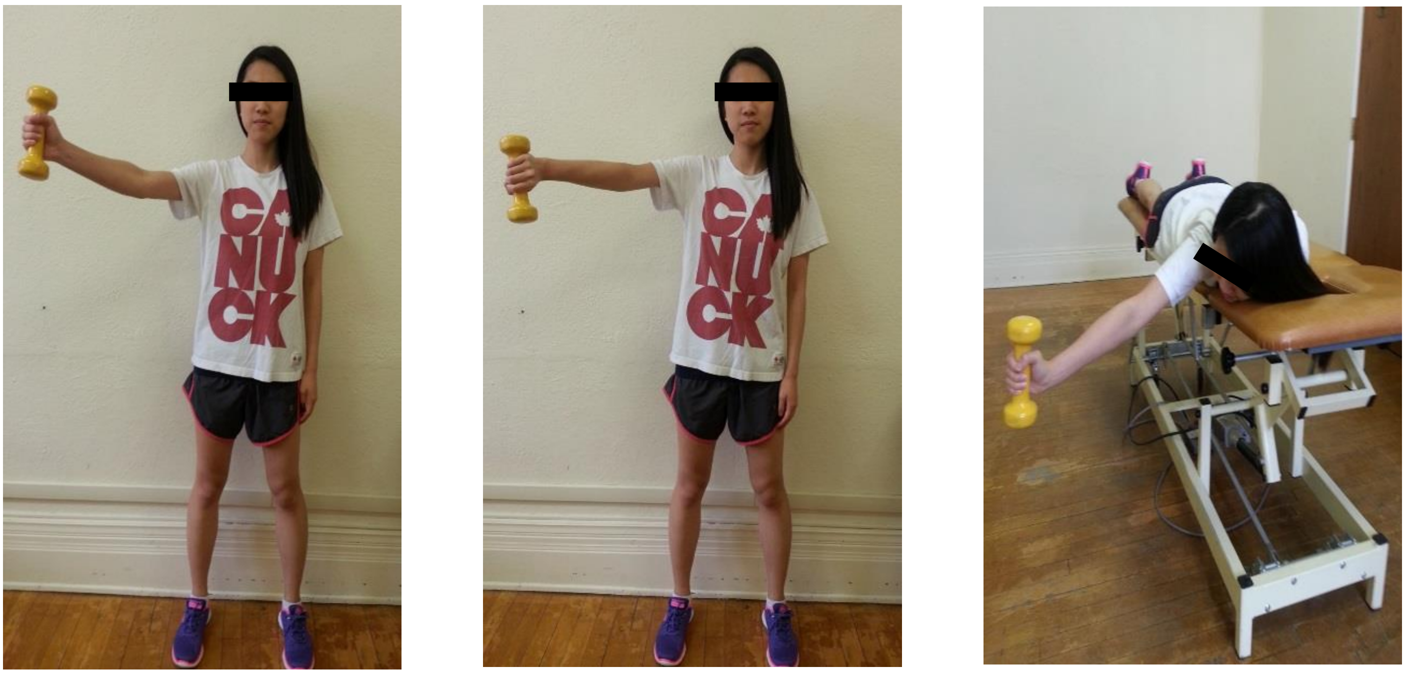
4.2 Methodology

Ethics approval was obtained from Biomedical Ethics Research Board at the University of Saskatchewan (BioREB #11-55). Participants were recruited via advertisements posted across the university campus and on the university website. Potential participants contacted the investigator by email or telephone and were screened for inclusion. Participants were eligible if they had normal upper limb function with no previous shoulder injury and had not participated in any regular physical activity or upper body strength training program (not more than 2 times/week) for the last five months. History of injury and resistance training experience for the last five months was self-reported by the participants. The dominant upper extremity was determined using the Waterloo Handedness Questionnaire (WHQ) (see Appendix 1). The 10-item version of WHQ is scored from -20 to +20 where negative score indicated left-handedness and positive score indicated right-handedness. Participants were informed about the study and written consent was obtained prior to the commencement of any data collection.

4.2.1 Exercise Protocol

Participants were randomly assigned to one of the following three exercise groups: full-can (FC), empty-can (EC) and prone horizontal abduction (PHA). For the FC and EC, participants abducted their arm in the standing position from 0-90˚ in the scapular plane with glenohumeral joint in full external rotation (thumb pointed towards ceiling) and full internal rotation (thumb pointed towards the ground) respectively. For the PHA, participants horizontally abducted their arm from 0-90˚ at 100˚ of glenohumeral abduction and full external rotation in prone lying (Figure 4.1). Scapular plane was defined as 30˚ anterior to the frontal plane of thorax (Boettcher et al., 2009). These exercises were chosen based on a review of the literature and frequency of use in clinical practice (Sciascia et al., 2012).

The exercise protocol adapted from Kim et al. (2014) included 8 weeks of strength training with 3 training sessions per week. The training sessions were separated by a minimum of 48 hours. Each session involved 4 sets of exercises for the first four weeks (weeks1-4) and 6 sets for the last four weeks (weeks 5-8), with each set consisting of 8 repetitions. A rest period of 30 seconds was provided in between each set to minimize fatigue. Participants performed exercises with a handheld dumbbell equal to 80% of their 10 repetition maximum (10 RM) for the first four weeks and 90% of their 10 RM in the last four weeks. The 10 RM was determined as the maximum weight the participant could lift 10 times in full-can, empty-can or prone horizontal abduction exercise, depending on the group assigned, with proper form (Reinold et al., 2007). The training was primarily concentric although each participant had to control the descent of the arm and weight which required eccentric control. Participants were instructed to complete the concentric phase of the exercise in 2 seconds and eccentric phase in one second. A warm-up program before 10RM testing was performed using a light weight dumbbell that allowed the participants to easily perform 8-10 repetitions. In order to ensure proper body positioning and prevent any compensatory movements while performing the exercises, the training sessions were performed under the supervision of the principal investigator (RS). The scapular positioning was maintained in slight retraction during the exercise training in all the groups as the protracted scapula has been shown to reduce the force producing capacity in the shoulder (Kibler et al., 2006; Smith et al., 2002). All participants were asked to maintain their normal daily lifestyle throughout the study.



(a) **(b)** **(c)**

Figure 4.1 (a) Full-can exercise. Shoulder abduction in the plane of scapula with full external rotation
(b) Empty-can exercise. Shoulder abduction in the plane of scapula with full internal rotation
(c) Prone horizontal abduction exercise. Shoulder horizontal abduction at 100° of abduction with full external rotation

4.2.2 Ultrasound Imaging

Architectural parameters of the supraspinatus muscle belly were captured using a portable LOGIQ e BT08 GE Healthcare Ultrasound Scanner (GE Medical Systems, Milwaukee, Wisconsin, USA) with a 12 MHz linear array (38 mm) transducer. Scans were performed according to the previously validated protocol outlined by Kim et al. (2010) at weeks 0, 4 and 8 of the training program. Scans at weeks 4 and 8 of training were conducted after 48 hours of the final training session of that training period. To ensure consistency, all the scans were performed by a single trained investigator (RS). The US transducer was held perpendicular to the plane of the muscle fiber bundles and minimum pressure was used to take images to avoid any deformation of the tissue.

During the ultrasound scanning, participants were seated on an adjustable chair with their back supported and feet flat on the ground. Sufficient water-soluble gel was applied on the skin area to be scanned to aid acoustic coupling and remove friction between the skin and transducer. The images of the anterior region of supraspinatus were taken in two states: relaxed and active or contracted. For the relaxed state, participant's arm was at 0˚ glenohumeral abduction i.e. by the side of the body and palm facing medially. For the active (contracted) state, arm was held at 60˚ glenohumeral abduction. Panoramic US images were taken to scan the fiber bundles within the anterior region and sagittal images were acquired to capture the thickness of the muscle. Approximately 15 images were taken in each state.

All the images taken were saved on the US unit for later analysis. Parameters measured from saved images were: FBL, PA and MT. One image with the clearest fiber bundles in the middle part which forms the majority of the anterior region, was chosen. The fiber bundles in which medial and lateral attachment ends were apparent and that could be seen along the majority of its length were used. As outlined in the protocol by Kim et al. (2010), FBL was measured as the distance between the medial and lateral attachment sites, and PA as an angle formed by the fiber bundles with the intramuscular tendon of the muscle (Figure 4.2). MT was computed according to the protocol outlined in a recent study by Yi et al. (2012). As outlined in their protocol, two lines were drawn on the skin, one along the scapular spine and another along the acromion. The point where two lines intersected was marked as acromion angle. Coracoid process was also marked and connected with the acromion angle. The scapular notch was identified with the US probe parallel to the muscle fibers. The probe was rotated and positioned parallel to the line connecting the coracoids process and acromion angle, with scapular notch placed at the center of the monitor. The acoustic shadowing of clavicle on one side and that of scapular spine on the other side were used as anterior and posterior borders respectively. The horizontal distance was measured between the two borders and the midpoint of this distance was marked. The vertical distance measured by drawing a line between the superior and inferior borders of the muscle passing through the midpoint provided the thickness of supraspinatus.

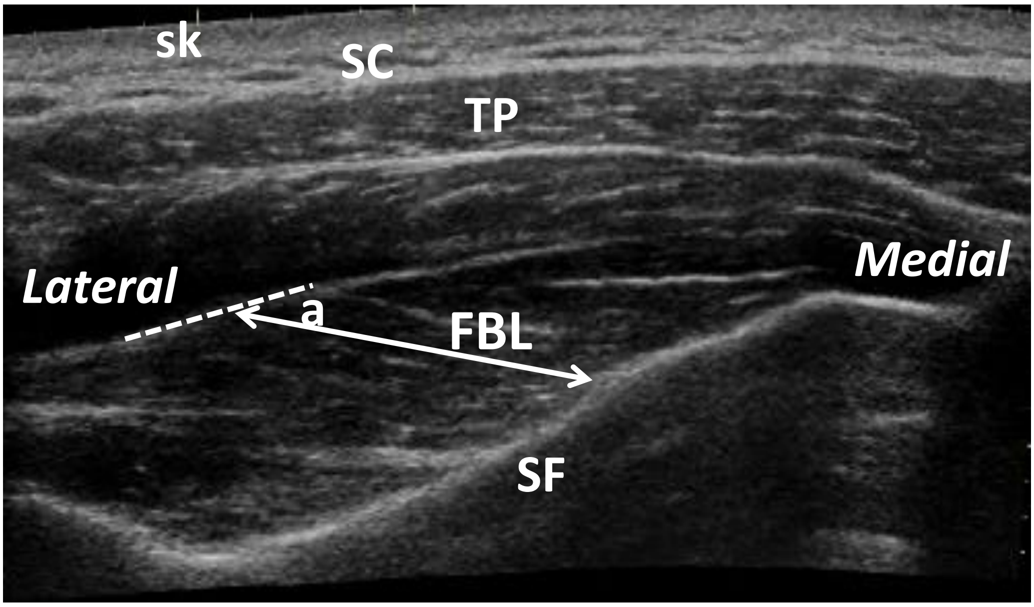


Figure 4.2 Panoramic US scan of right normal supraspinatus. One fiber bundle from the anterior region is demarcated by a white line, a (pennation angle), FBL (fiber bundle length), sk (skin), SC (subcutaneous tissue), TP (trapezius muscle), SF (supraspinous fossa), •• (intramuscular tendon)

4.2.3 Strength testing

A portable hand-held dynamometer (Lafayette Manual Muscle Tester, Model 01163, IN, USA) was used to record the maximal isometric shoulder abduction strength. The validity and reliability of the hand-held dynamometer (HHD) has been published previously (Bohannon, 1986; Magnusson et al., 1990). Shoulder abduction strength of each participant was tested in three different positions: arm in 0˚ glenohumeral abduction and full external rotation pushing against resistance in the scapular plane (strength testing in neutral full-can position); arm in 0˚ glenohumeral abduction and full internal rotation pushing against resistance in the scapular plane (strength testing in neutral empty-can position); arm resting at 100˚ forward flexion and external rotation pushing against resistance in the horizontal abduction plane (strength testing in neutral prone horizontal abduction position). For all strength testing positions, the participant was standing and the HHD was placed just proximal to the ulnar styloid process (Magnus et al., 2014; Reinold et al., 2008). Participants received standard verbal encouragement to apply maximum effort and two 3 seconds long contractions were recorded in each position. The average of the two contractions was recorded as a peak value (in kilograms). Participants were instructed to progressively increase the force and reach their maximal force at the end of 3 seconds. To minimize fatigue, a rest period of 30 seconds between each repetition and a rest of 60 seconds was provided between each testing position. An additional repetition was performed if any body movement or compensation was observed. The same order of testing was followed for each participant (testing in full-can position, followed by empty-can and prone horizontal abduction positions) during each testing session.

4.3 Data Analysis

The architectural and strength data were analysed using SPSS (version 20; SPSS Inc., Chicago, IL, USA). Data were screened for normality, skewness and kurtosis before parametric tests were applied. For comparison of baseline differences in age and measured parameters (FBL, PA, MT and strength) between the training groups, one-way analysis of variance (ANOVA) was used. Factorial analysis of variance (ANOVA) with repeated measures was used to compare the training groups (FC, EC and PHA) across 3 time points (pre-training, at 4 weeks and post-training) for all the measured variables (FBL, PA and MT). Separate ANOVAs were used for relaxed and contracted states. In case of violation of sphericity, Greenhouse-Geisser adjustment was applied (Mauchly's test of sphericity, $p<0.05$). If significant main effects or interactions were detected, simple main effects analysis was carried out using one-way ANOVA and Tukey's post hoc tests. Student's paired *t*-tests were also used to make within training group comparisons for all the measured variables between different time points. Means and standard deviations of data are reported (Tables 4.1 & 4.2). Statistical significance was set at $p<0.05$ with Bonferroni adjustments made where appropriate.

4.4 Results

Thirty four healthy adults (15 males and 19 females), with mean age of 29.8 ± 7.3 years, volunteered to participate in the study. All the participants had post-secondary education. There were 30 right-handed and 4 left-handed participants in the study. Three participants dropped out due to the time commitment of the study. No adverse events occurred as a result of the training protocol. There were no significant differences between the groups at baseline for age, all the architectural parameters (FBL, PA and MT) and strength.

4.4.1 Fiber bundle length

There was a significant group X time interaction ($p=0.013$) and a main effect of time ($p<0.001$) for mean FBL in the relaxed state. No significant differences for mean FBL between the groups were shown at any time point. Within the groups; however, mean FBL decreased after 4 weeks of training in the FC ($p=0.001$) and EC ($p=0.008$), but it did not change in the PHA ($p=0.12$). No changes in the mean FBL were observed from 4 to 8 weeks of training in any group (Figure 4.3).

For the contracted state, there was a significant group X time interaction ($p=0.023$) and a main effect of time ($p<0.001$). Similar to the relaxed state, no significant differences for the mean FBL were found between the groups at any time point ($p>0.05$). Within the groups, mean FBL reduced significantly from 0 to 4 and 4 to 8 weeks of training in the FC (0 to 4 weeks, $p=0.008$; 4 to 8 weeks, $p=0.044$) and EC (0 to 4 weeks, $p=0.013$; 4 to 8 weeks, $p=0.039$). However, no differences were found in the PHA (0 to 4 weeks, $p=0.49$; 4 to 8 weeks, $p=0.68$).

When Bonferroni adjustments were made, no significant differences were detected in the mean FBL from 4 to 8 weeks of training ($p>0.017$) in the FC and EC in the contracted state.

4.4.2 Pennation angle

A significant time main effect was seen for both relaxed ($p<0.001$) and contracted ($p<0.001$) states, but no significant differences between the groups were found at any time point ($p>0.05$).

4.4.3 Muscle thickness

There was a significant main effect of time for mean MT in both relaxed ($p<0.001$) and contracted ($p<0.001$) states. However, no significant differences were found between the groups at week 4 or week 8 of training ($p>0.05$).

4.4.4 Strength

There was a significant group X time interaction ($p=0.008$) and a main effect of time ($p<0.001$) when the testing was performed in prone horizontal abduction position. A significant increase in strength was observed at week 4 in all the groups (FC, $p=0.005$; EC, $p=0.014$; and PHA, $p<0.001$), but it increased further only in the PHA ($p=0.004$) at week 8 (Figure 4.4). Also, there was a significant difference between EC and PHA at week 8 ($p=0.023$).

When Bonferroni adjustments were made for multiple comparisons, significant differences between EC and PHA were not seen.

Table 4.1 Architectural parameters for supraspinatus before and after training. All values are means (± SD)

		Full-Can group			Empty-Can group			Prone Horizontal Abduction group		
Variable	*State*	*Pre-training*	*Week 4*	*Week 8*	*Pre-training*	*Week 4*	*Week 8*	*Pre-training*	*Week 4*	*Week 8*
Fiber Bundle Length (cm)	Relaxed	5.12 (0.63)	4.58 (0.55)*	4.44 (0.52)*	5.22 (0.74)	4.63 (0.63)*	4.46 (0.61)*	4.86 (0.30)	4.77 (0.40)	4.70 (0.49)
	Active	3.97 (0.56)	3.70 (0.43)*	3.45 (0.42)*	4.25 (0.71)	3.89 (0.52)*	3.58 (0.48)*	3.92 (0.42)	3.86 (0.53)	3.80 (0.43)
Pennation Angle (°)	Relaxed	23.73 (1.70)	26.07 (1.24)	27.41 (1.99)	22.35 (2.38)	24.62 (1.81)	27.15 (2.37)	22.63 (2.30)	24.92 (1.69)	26.21 (1.99)
	Active	26.93 (2.47)	29.41 (2.94)	30.85 (2.10)	27.10 (2.23)	28.37 (1.79)	31.10 (2.30)	27.82 (2.05)	28.29 (2.18)	30.13 (2.61)
Muscle Thickness (cm)	Relaxed	2.07 (0.29)	2.16 (0.27)	2.24 (0.27)	1.99 (0.37)	2.01 (0.38)	2.086 (0.40)	1.93 (0.17)	2.05 (0.18)	2.12 (0.20)
	Active	2.21 (0.28)	2.29 (0.26)	2.37 (0.28)	2.10 (0.38)	2.15 (0.38)	2.21 (0.38)	2.11 (0.20)	2.20 (0.21)	2.27 (0.21)

For FBL, there was a significant group X time interaction (relaxed, p=0.013; contracted, p=0.023) and a main effect of time (p<0.001). A significant time main effect was seen for mean PA for both relaxed (p<0.001) and contracted (p<0.001) states. There was a significant main effect of time for mean MT in both relaxed (p<0.001) and contracted (p<0.001) states. * Significantly different than pre-training within the same group (adjusted values) (relaxed, p<0.013; contracted, p<0.017).

Table 4.2 Abduction strength (kgs) before and after training. All values are means (± SD)

		Full-Can group			Empty-Can group			Prone Horizontal Abduction group		
Variable	*Position*	*Pre-training*	*Week 4*	*Week 8*	*Pre-training*	*Week 4*	*Week 8*	*Pre-training*	*Week 4*	*Week 8*
Abduction Strength	Full-Can	10.86 (3.67)	12.33 (3.73)*	13.54 (3.92)*	10.20 (3.89)	11.43 (3.72)*	12.20 (3.81)*	11.48 (2.86)	12.65 (2.93)*	13.85 (2.46)*
	Empty-Can	8.76 (2.84)	9.23 (3.07)*	9.92 (3.02)*	7.95 (3.04)	8.67 (3.63)*	9.61 (4.17)*	8.25 (1.74)	9.20 (1.87)*	10.64 (2.51)*
	Prone Horizontal Abduction	9.52 (2.71)	10.15 (2.51)*	10.76 (2.40)*	8.42 (3.07)	9.03 (3.21)*	9.38 (3.17)*	10.21 (1.72)	11.56 (1.88)*	12.52 (2.22)* #

There was a significant group X time interaction (p=0.008) and a main effect of time (p<0.001) when the testing was performed in prone horizontal abduction position. * Significantly different than pre-training within the same group (p<0.017). # Significantly different than week 4 within the same group (p=0.004).

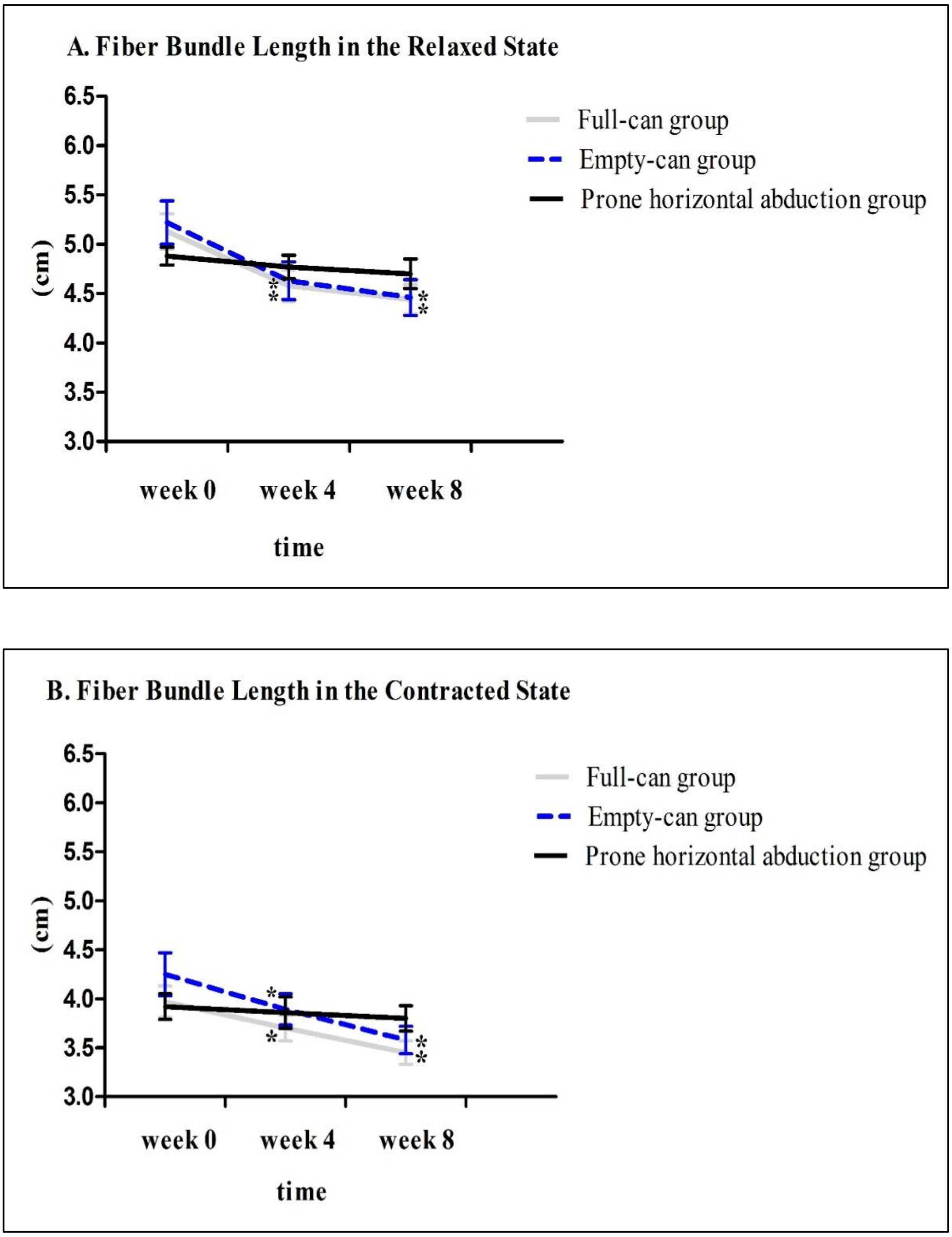


Figure 4.3 (A & B) Fiber Bundle Length changes in the relaxed and contracted states. Values are means (±SE). There was a significant group X time interaction (relaxed, $p=0.013$; contracted, $p=0.023$) and a main effect of time ($p<0.001$).
* Significantly different than week 0 (for full-can and empty-can groups) (Bonferroni adjusted for multiple comparisons $p<0.05/3=0.017$).

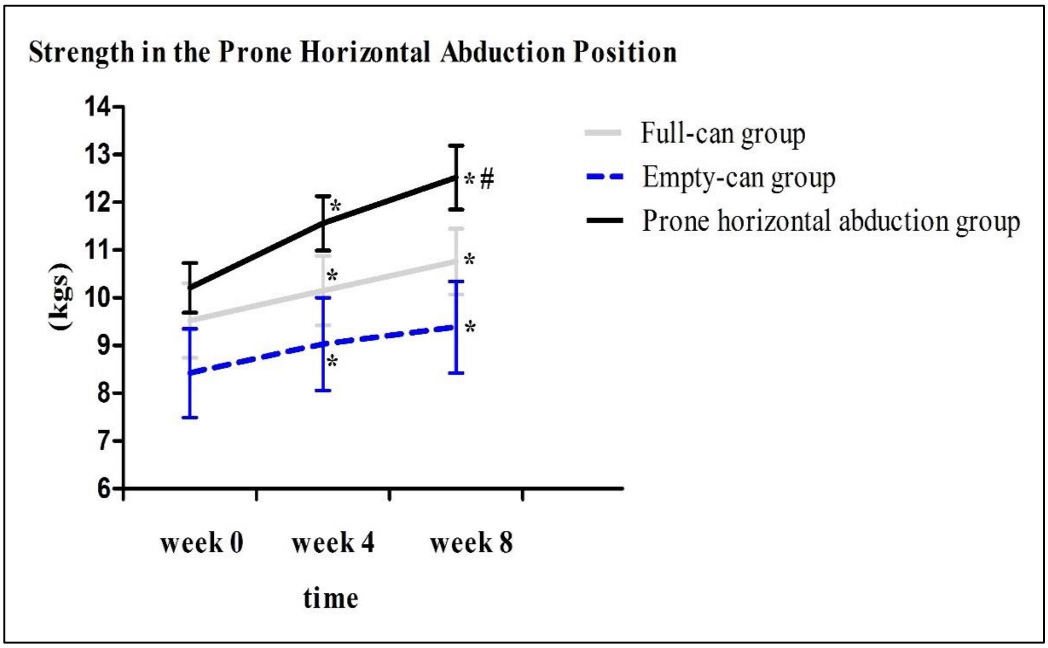


Figure 4.4 Strength change in Prone Horizontal Abduction position. Values are means (±SE). There was a significant group X time interaction (p=0.008) and a main effect of time (p<0.001). ***** Significantly different than week 0 (p<0.017). [#] Significantly different than week 4 (p=0.004).

4.5 Discussion

This is the first study, to our knowledge, to examine and compare three supraspinatus strengthening exercises based on architectural changes within the muscle. To date, numerous studies have investigated and compared supraspinatus strengthening exercises using EMG, shoulder and scapular kinematics, and MRI; however, consensus regarding the most effective exercise is still lacking. It is widely recognized that a muscle's function cannot be predicted accurately without investigating its architecture (Lieber & Fridén, 2000). Therefore, through this study, we attempted to investigate and add to the scientific basis of commonly performed supraspinatus strengthening exercises by examining its fiber bundle architecture in response to resistance training.

The most notable finding of the present study was that there was a significant decrease in FBL after 4 weeks of training in the full-can and empty-can; however, no significant changes in FBL were observed in the PHA at any time point in the relaxed as well as contracted states (Figure 4.3). The decrease in FBL of supraspinatus after conventional strength training found in this study is consistent with previous supraspinatus strengthening study (Kim et al., 2014). The preservation of FBL in prone horizontal abduction may have several important functional and clinical implications. Fiber bundle length represents the number of sarcomeres arranged in series and indicates the excursion potential and contraction velocity of the muscle (Lieber & Ward, 2011). In a muscle with shorter FBL, sarcomeres would be forced to operate over a larger range putting them in a disadvantageous position on the length-tension curve (Ward et al., 2010). Therefore, maintenance of FBL in the PHA with a concurrent increase in strength following resistance training would allow the sarcomeres to optimally contract, producing higher velocity contractions with greater force over a larger joint range of motion (Kim et al., 2014).

We speculate several reasons for this difference in FBL change between the three positions investigated. First, differences in architectural adaptations may be attributed to large differences between movement patterns (Blazevich et al., 2003). Of the three movements investigated in our study prone horizontal abduction involved a unique movement pattern compared to the full-can and empty-can exercises. Another possible explanation for differences in FBL changes could be provided by the mechanical properties of the supraspinatus tendon that might have changed differently between the groups. The tendon loading may be higher during prone horizontal abduction than full-can and empty-can which may have increased the stiffness of tendon after 4 weeks of training in the prone horizontal abduction, preventing shortening of muscle fibers. Previously, the mechanical properties of tendons including tendon stiffness of lower limb muscles, particularly of quadriceps and hamstrings, have been studied extensively (Kubo et al., 2001; Kubo et al., 2002; Maganaris et al., 2004). The reported temporal response for increased tendon stiffness varies from 6 to 16 weeks of resistance training between the studies. This variation in temporal response has been attributed to difference in muscle groups and different training modes used in the studies (Kubo et al., 2002). Supraspinatus is architecturally complex with intra- and extra-muscular tendons (Kim et al., 2007) and may exhibit different tendon properties in response to resistance training than that of lower limb muscles. The muscle architecture of supraspinatus, specifically the anterior region which was investigated in this study, is circumpennate whereas the rectus femoris and vastus lateralis are bipennated muscles (Kim et al., 2014).

Lastly, the adaptation of FBL after resistance training has been suggested to be influenced by training range of motion and contraction velocity rather than by contraction mode (Blazevich et al., 2007). In our study, it is possible that loading was achieved through a greater range in the prone horizontal abduction movement; beyond what participants would do on a regular basis or during daily life functional activities. Further investigation is needed to clarify these speculations.

Our results of increased PA after resistance training are in agreement with previous strength training studies of upper (Kawakami et al., 1995; Kim et al., 2014) and lower limb muscles (Aagaard et al., 2001; Blazevich et al., 2007). An increase in PA affect the force producing capacity of the muscle by enabling more contractile material to be attached within a given area (Gans & Bock, 1965), and increasing the architectural gear ratio that allows fiber bundles to produce forces at optimal lengths and shortening velocities (Brainerd & Azizi, 2005). The PA increased after 4 weeks of training and continued to increase after 8 weeks of training in all the groups, with no differences between the groups. Consistent with PA, a significant increase in MT was also found in all the groups after 4 and 8 weeks of strength training in both relaxed and active states, with no group differences. The increase in PA and MT found in this study indicates the strong relationship between the adaptation of PA and muscle size with resistance training (Kawakami et al., 1993; Kawakami et al., 1995).

An increase in muscle strength in response to resistance training is closely associated with neural adaptation, muscle hypertrophy and increased force production (Chilibeck et al., 1999; Narici et al., 1989). Although there was a significant effect of strength training for all the 3 groups in all the positions of testing, a larger training effect was observed in prone horizontal abduction when the testing was done in prone horizontal abduction position (Figure 4.4). The greater increase in strength from 0-4 weeks and a significant increase from 4-8 weeks in the PHA could indicate increased neuromuscular adaptation and a role of motor learning (Carroll et al., 2001). Furthermore, a significant gain in strength seen in PHA after 8 weeks of training when the testing was performed in prone horizontal abduction position is suggestive of training mode specificity (Wilson et al., 1996). The results also suggest that full-can and empty-can training does not transfer to the prone testing mode and that prone horizontal abduction augments strength in multiple modes, which is desirable in most clinical and rehabilitation settings.

Since all the rotator cuff muscles originate from the scapula, the rotator cuff activity is markedly influenced by the static position and dynamic motion of the scapula. Based on scapular kinematic data, full-can has been suggested to be a preferred exercise over the empty-can to strengthen supraspinatus (Thigpen et al., 2006). Internal rotation of the humerus during empty-can movement has been found to decrease the size of subacromial space due to a marked increase in internal rotation and anterior tipping of the scapula causing shoulder impingement, whereas full-can has led to opposite movements of the scapula and an increase in the subacromial space (Thigpen et al., 2006). The scapular positioning during the prone horizontal abduction exercise has also been suggested to increase the subacromial space and provide a favourable position for supraspinatus strengthening (Reinold et al., 2009).

Previously, several EMG studies have found high amount of supraspinatus activation level during prone horizontal abduction exercise (Blackburn et al., 1990; Reinold et al., 2004; Worrell et al., 1992). Other than supraspinatus, prone horizontal abduction has also been shown to produce high activity of the lower trapezius muscle. The inferomedial-directed fibers of the lower trapezius could produce posterior tipping and external rotation of the scapula (Ludewig et al., 1996) which may lower the risk of subacromial impingement. In addition, high EMG activity of teres minor and infraspinatus was also found during PHA in previous studies (Blackburn et al., 1990; Malanga et al., 1996; Takeda et al., 2002) which provides stability to the shoulder joint by resisting the superior and anterior translation of humeral head. The activation of rotator cuff and scapulothoracic muscles during prone horizontal abduction suggest that this exercise may be implemented to strengthen multiple shoulder muscles simultaneously.

Previously, Reinold et al. (2007) recommended the full-can exercise over empty-can and prone horizontal abduction despite the similar supraspinatus activity found in their study. They argued the high amount of EMG activity shown in middle and posterior deltoid with empty-can and prone horizontal abduction could be disadvantageous and increase the risk of subacromial impingement (Boettcher et al., 2009; Malanga et al., 1996; Reinold et al., 2004; Reinold et al., 2007; Townsend et al., 1991). Therefore, it was suggested that these exercises may be detrimental for the patients with compromised rotator cuff function which may fail to provide the dynamic stability to the glenohumeral joint and counteract the superior pull of deltoid (Reinold et al., 2007). Furthermore, empty-can movement may provoke pain in patients with shoulder impingement as it diminishes the subacromial space (Brossmann et al., 1996; Graichen et al., 1999) which makes it a less desirable exercise compared to other supraspinatus strengthening exercises. In contrast to the findings of Reinold et al. (2007), Takeda et al. (2002) found significantly higher activity of the anterior and middle deltoid after full-can and empty-can compared to prone horizontal abduction by evaluating T2 relaxation time using MRI. The findings of Takeda et al. (2002) were partially supported by Boettcher et al. (2009), who reported similar activity of middle deltoid in the three positions and a higher activity of anterior deltoid in full-can and empty-can. These disparities in the results warrant further investigation of the deltoid activity during supraspinatus strengthening exercises. In a more recent study, Reinold et al. (2009) has indicated that the movements that produce high levels of middle deltoid (e.g. empty-can) and/or anterior deltoid activity are disadvantageous than those activating the posterior deltoid activity (e.g. prone horizontal abduction). Therefore, PHA can be used effectively to strengthen rotator cuff. The maintenance of FBL and increased strength in the prone horizontal abduction position found in our study also support the findings of previous studies that prone horizontal abduction may be a more effective exercise to strengthen the supraspinatus.

4.5.1 Limitations of the study

There were a few notable limitations in this study which should be considered in future research studies. First, sample size was small which did not allow us to apply multivariate analyses and may also have contributed to the lack of statistical differences between the groups. We recruited 34 participants with approximately 11 participants in each group. The small sample size was in part due to long term commitment for the study; participants needed to complete 8 weeks of strength training with 3 sessions per week under the supervision of a principal investigator. Moreover, participants were not allowed to perform any upper body strength training during the study. A second limitation is the short duration of training. Even though strength training programs up to 8 weeks have been shown to induce significant architectural changes in the muscles of upper and lower limbs (Blazevich et al., 2003; Kim et al., 2014; Kubo et al., 2002), longer training periods might have shown more significant results between the groups. Lastly, in this study, only healthy participants were recruited and we did not evaluate the muscle architecture of other muscles such as deltoid which has been shown to be fairly active in the EMG studies while performing empty-can and prone horizontal abduction exercises. Assessing the architecture of surrounding muscles would have provided more information on the effectiveness of these exercises and confirmed the findings of previous EMG studies.

4.6 Conclusion

The primary findings of the current study demonstrated significant changes in the architectural parameters of the supraspinatus and shoulder abduction strength following resistance training in all the groups. Specifically, strength training using prone horizontal abduction was effective for maintaining FBL and facilitating increases in strength in multiple modes indicating that it may be a more effective exercise for supraspinatus strengthening. However, the results should be interpreted with caution when dealing with patients with rotator cuff problems.

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Appendices

Table of Appendices

Appendix 1

Waterloo Handedness Questionnaire

INSTRUCTIONS: Please indicate your hand preference for the following activities by circling the appropriate response. Think about each question. You might try to imagine yourself performing the task in question. Please take your time.

If you use one hand 95% of the time to perform the described activity, then circle right always or left always as your response.

If you use one hand about 75% of the time, then circle right usually or left usually.

If you use both hands roughly the same amount of time, then circle equally.

1. Which hand do you use for writing?
Left Always Left Usually Equally Right Usually Right Always

2. With which hand would you unscrew a tight jar lid?
Left Always Left Usually Equally Right Usually Right Always

3. In which hand do you hold a toothbrush?
Left Always Left Usually Equally Right Usually Right Always

4. In which hand would you hold a match to strike it?
Left Always Left Usually Equally Right Usually Right Always

5. Which hand would you use to throw a baseball?
Left Always Left Usually Equally Right Usually Right Always

6. Which hand do you consider the strongest?
Left Always Left Usually Equally Right Usually Right Always

7. With which hand would you use a knife to cut bread?
Left Always Left Usually Equally Right Usually Right Always

8. With which hand do you hold a comb when combing your hair?
Left Always Left Usually Equally Right Usually Right Always

9. Which hand do you use to manipulate implements such as tools?
Left Always Left Usually Equally Right Usually Right Always

10. Which hand is the most adept to picking up small objects?
Left Always Left Usually Equally Right Usually Right Always

CHAPTER FIVE

SUMMARY OF FINDINGS AND FUTURE DIRECTIONS

5 Summary of findings and future directions

The broad aim of this dissertation was to gain an in-depth understanding of the architecture of the supraspinatus and determine the effect of surgical repair and strength training exercises on the architecture of the supraspinatus. With the knowledge gained from the three studies conducted in this dissertation, the overall goal was to provide a scientific rationale for improving rehabilitative protocols for rotator cuff tears. Considering the functional and clinical importance of the supraspinatus muscle, several objectives were devised.

The objectives of this dissertation were to: 1) synthesize the evidence on the quality of supraspinatus architectural studies and highlight the key aspects that should be considered while performing skeletal muscle architecture studies, 2) understand the impact of surgical repair on the structural and functional recovery of the supraspinatus, and 3) provide a scientific rationale behind choosing an exercise to strengthen supraspinatus by investigating its muscle architecture. The approaches used to achieve these objectives include a systematic review to address the first objective, an observational prospective cohort study in patients to address the second objective and a randomised control trial study in healthy persons to address the third objective.

5.1 Principal Findings

Chapter two systematically reviewed and evaluated the quality of 18 human cadaveric dissection studies on the architecture of the normal supraspinatus. Meta-analyses was not conducted due to several methodological limitations and heterogeneous nature of the studies. However, a synthesis of best evidence was conducted by assessing the methodological quality of the studies using a specially designed checklist consisting of eight items. It was found that there is a wide disparity of reported architectural values for the supraspinatus between the previous human cadaveric studies with only a few studies recognizing the complexity of the muscle. Furthermore, the methodological quality was found to be low in 12 of the 18 studies due to several methodological limitations and lack of clear descriptions of the muscle architectural parameters which limits the clinical application of the reported data in these studies. This study was important to conduct as the knowledge of the normal architecture is crucial to understand the changes of muscle that occur due to injury, surgical repair and strength training.

Successful management of rotator cuff tears is often dependent on the surgical intervention and appropriately planned rehabilitation. Chapter 3 investigated and compared the architecture of supraspinatus pre- and post-surgical repair at different time points to elucidate the impact of repair on the recovery of the muscle. It was found that the FBL was significantly greater after one month of surgery which could be attributed to the tension applied onto the muscle and tendon during the repair. This stretching of the musculotendinous unit may damage the sarcomeres and compromise the contractile ability of the muscle. The FBL remained lengthened even after three months of the repair, thus, the exercise loads should be kept low to enhance muscle recovery and avoid re-tears. At six months following repair, the shortening of FBL and increase in PA indicate that the muscle is adapting to its normal architecture.

As mentioned earlier, rehabilitation is an important component in the structural and functional recovery of tendon tears. Therefore, the choice of exercise is of utmost importance to restore the muscle strength. Chapter 4 presented the results of resistance training on the architecture of supraspinatus using three commonly prescribed supraspinatus strengthening exercises. Muscle hypertrophy and an increase in strength was observed in all the groups after resistance training. It was observed that the FBL of the supraspinatus decreased after 4 and 8 weeks of training in the full-can and empty-can groups. However, it was maintained in the prone horizontal abduction group after training. Furthermore, an increase in shoulder abduction strength was found after 4 and 8 weeks of training in the prone horizontal abduction group when the testing was performed in the prone horizontal abduction position. The maintenance of FBL with increase in strength may allow the muscle to generate forces over a large range. Overall, the findings indicate that the prone horizontal abduction may be more beneficial exercise for strengthening supraspinatus.

5.2 Future Directions

The findings of the dissertation could be used to advance future muscle architectural studies and form the basis of several anatomical, muscle modelling and clinical studies. The possible future directions related to each study are outlined below:

Manuscript #1 (Chapter 2)

- Future muscle architectural studies should consider the key methodological factors recognized in our systematic review to generate more confidence into the reliability and accuracy of data sets.
- Future systematic reviews of the muscle architectural studies should aim to follow comprehensive Prisma and Cochrane guidelines.

Manuscript #2 (Chapter 3)

- Larger sample size should be considered which will allow for multiple analyses and increase the chances of statistically significant findings.
- Post-surgical patients should be examined for longer than six months to measure architectural parameters and strength gains to better understand the functional implications of surgical techniques.
- Sarcomere length should be investigated along with architectural features to gain more insight into the muscle function and effect of increased repair tension on the recovery of the muscle.
- The potential benefits of rotator cuff repairs reinforced with synthetic grafts or allografts including structural support and improved healing rates have been suggested previously. In order to achieve greater validation, architectural changes following these surgical procedures should be investigated.

Manuscript #3 (Chapter 4)

- Consider larger sample size and longer periods of resistance training to gain more insight into the muscle's function and effect of movement pattern following resistance training. Also, muscle architecture should be assessed after a detraining period to evaluate the long term effects of these exercises.
- The architecture of the muscle is altered with injury which in turn changes the functional properties of the muscle. Hence, understanding the effect of these exercises on muscle architecture in patients with shoulder instability and rotator cuff problems would further guide clinicians to select optimal supraspinatus strengthening exercises which may enhance the healing rate without putting undue stress on the soft tissue structures.
- Since the posterior region of the muscle is functionally important, investigating its architecture following strength training will further inform rehabilitative strategies.
- Increased supraspinatus activity has also been noted in several other exercises that are not thought of as rotator cuff exercises including rowing exercises and push-up exercises. Therefore, investigating the supraspinatus architectural changes following different exercises would allow therapists to design appropriate and efficient rehabilitation programs.