Rotator cuff tendons of the shoulder joint : anatomy and investigation of strain profile

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**NANYANG
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**ROTATOR CUFF TENDONS OF THE SHOULDER JOINT:
ANATOMY AND INVESTIGATION OF STRAIN PROFILE**

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SCHOOL OF MECHANICAL AND AEROSPACE ENGINEERING

2013

**ROTATOR CUFF TENDONS OF THE SHOULDER JOINT:
ANATOMY AND INVESTIGATION OF STRAIN PROFILE**

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ABSTRACT

The prevalence of rotator cuff tears found in elderly patients in Singapore has led to an appreciation of the importance of studying its causes and appropriate treatment. The objective of this project is to investigate the effect of arm positions, tendon tears and surgical repair on the strain profile of the rotator cuff tendons.

Nine fresh-frozen shoulders were tested using displacement variable reluctance transducers (DVRTs) to measure the strains of the supraspinatus, infraspinatus and subscapularis tendons simultaneously with the glenohumeral joint intact at various arm positions. This was followed by simulated tears and surgical repairs.

The rotator cuff strains showed varying trends at different arm positions. The strain difference between the articular and bursal side of the supraspinatus implied the occurrence of shearing which may cause intratendinous tears. A full thickness tear at the anterior supraspinatus increased the strain at the posterior supraspinatus. Single-row repairs increased the strain difference between the articular and bursal surfaces of the tendon. It was shown that double-row repairs restored the strains to the intact strain condition and thus may be more efficient for tendon healing than single-row repairs. Elevation of arm at higher angles should be avoided after surgical repairs due to the high differential strains between the two surfaces of the supraspinatus.

The footprint areas and dimensions of the rotator cuff tendons from nineteen Asian shoulder specimens were collected. The knowledge of the average footprint area of each tendon helps the surgeon to restore torn tendons to their functional anatomic positions.

ABSTRACT

Tensile tests were conducted to obtain the elastic modulus of the tendons. The strain, anatomical data and tensile properties collected were used in the validation of a three-dimensional finite element model that was developed. The FE model showed similar trends in the strain as compared to the experimental results. High shear stresses were observed near the footprint within the supraspinatus. These stresses could initiate tears, propagate intratendinous defects and ultimately cause delamination of the tendon. From the FE model developed, it was observed that the strain varies linearly across the supraspinatus between the articular and bursal surface at elevated angles.

It is hoped that the results obtained from this study can be useful for the surgical treatment and rehabilitation of patients with rotator cuff tears.

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TABLE OF CONTENTS

TABLE OF CONTENTS

Abstract	1
Acknowledgement	3
Table of Contents	4
List of Figures	10
List of Tables	17

1 INTRODUCTION

1.1	Background	19
1.2	Objective and scope	20
1.3	Contributions	21
1.4	Experimental hypotheses	22
1.5	Organisation of report	22

2 SHOULDER COMPLEX

2.1	General anatomy of the shoulder complex	23
2.2	Glenohumeral joint	25
2.3	Rotator cuff	
	2.3.1 Dynamic stabilization	27
	2.3.2 Gross anatomy and function of rotator cuff	27
2.4	Anatomical position and movement of the shoulder complex	
	2.4.1 Definition of the anatomical position	29
	2.4.2 Resting position of the scapula	31

TABLE OF CONTENTS

2.4.3	Movement of glenohumeral joint	32
2.4.4	The Scapulohumeral rhythm	34
3	LITERATURE REVIEW	
3.1	Gross anatomy of rotator cuff	36
3.2	Histology of rotator cuff	40
3.3	Classification of rotator cuff tears	42
3.4	Incidence and prevalence of rotator cuff tears	44
3.5	Pathophysiology	46
3.6	Footprint and dimensional measurement of rotator cuff	50
3.7	Strain Studies on rotator cuff	
3.7.1	Effect of arm position and repair methods on strain in repaired rotator cuff	58
3.7.2	Strain studies relating to partial thickness tears on rotator cuff	61
3.8	Methods for measuring surface area	
3.8.1	Grids	68
3.8.2	Particle layer	69
3.8.3	Planar area	69
3.9	Biomechanical testing of rotator cuff tendons	
3.9.1	Factors affecting biomechanical experiments	70
3.9.2	Strain studies relating to tensile testing on rotator cuff	76
3.10	Finite element analysis on rotator cuff	78
3.11	Summary	92

TABLE OF CONTENTS

4 METHODOLOGY

4.1	Strain measurements of rotator cuff tendons	
4.1.1	Design of purpose-built rig	93
4.1.2	Cadaveric shoulder specimens	
4.1.2.1	Source	96
4.1.2.2	Specimen preparation and dissection	96
4.1.2.3	Storage of specimens after use	99
4.1.3	Calculations of loadings for individual muscles	100
4.1.4	Suturing and mounting of specimen	105
4.1.5	Differential variable reluctance transducers (DVRTs)	
4.1.5.1	Specifications of DVRTs	108
4.1.5.2	Insertions of DVRTs	110
4.1.6	Experimental Variables	
4.1.6.1	Arm positions	112
4.1.6.2	Rotator cuff tears	113
4.1.6.3	Rotator cuff repairs	114
4.1.7	Data collection	116
4.2	Anthropometry and footprint measurement	
4.2.1	Width and thickness	117
4.2.2	Length	118
4.2.3	Footprint	119

TABLE OF CONTENTS

4.3	Tensile test of rotator cuff	
4.3.1	Materials and equipment	123
4.3.2	Procedures	124
4.4	Finite element analysis of rotator cuff	128
4.4.1	Creating 3D representation from MRI	129
4.4.2	Exporting into Solidworks software	131
4.4.3	Preprocessing	134
4.4.4	Meshing	135
4.4.5	Defining material properties	137
4.4.6	Boundary and loading conditions	138
4.4.7	FE strain analysis	141
5	RESULTS	
5.1	Strain measurements of rotator cuff tendons	
5.1.1	Arm positions	142
5.1.2	Simulated tears	146
5.1.3	Repairs	148
5.2	Anthropometry and footprint measurement	
5.2.1	Width and thickness	149
5.2.2	Length	150
5.2.3	Footprint	151
5.3	Tensile test of rotator cuff tendons	153
5.4	Finite element analysis	154

TABLE OF CONTENTS

6 DISCUSSION

6.1	Strain measurements of rotator cuff tendons	161
6.1.1	Arm positions	161
6.1.2	Simulated tears	163
6.1.3	Repairs	164
6.1.4	Limitations	166
6.2	Anthropometry and footprint measurement	
6.2.1	Dimension of tendons	167
6.2.2	Footprint	168
6.2.3	Limitations	169
6.3	Tensile test of rotator cuff tendons	
6.3.1	Tensile test	170
6.3.2	Limitations	171
6.4	Finite element analysis	
6.4.1	Finite element analysis	172
6.4.2	Limitations	174

7 CONCLUSIONS AND FUTURE WORK

7.1	Conclusions	175
7.2	Future work	176
7.3	Publications	177

TABLE OF CONTENTS

Bibliography	179
Appendix	188

LIST OF FIGURES

List of Figures

2.1	Bones of the shoulder	23
2.2	Shoulder joints	24
2.3	Supporting layers of the glenohumeral joint	26
2.4	Muscles of the rotator cuff	28
2.5	The anatomical position showing the cardinal planes and directional terminology	30
2.6	The resting position of the scapula on the thorax	31
2.7	Axes of movement at the shoulder joint	33
2.8	Movements at the shoulder joint with respect to the plane of the glenoid fossa	34
3.1	Complete myotendinous cuff and capsule spread out after removed from scapula and humeral head	37
3.2	Dissection of cuff tendons, showing how the tendons converge as they insert on the humerus	39
3.3	Schematic diagram of a rotator cuff dissection through the supraspinatus (SS) and infraspinatus(IS) to demonstrate the 5-layer histologic configuration of the cuff	41
3.4	Classification of partial tears by location	42
3.5	Classification of partial tears by depth	43
3.6	Superior and posterior projections of the rotator cable and crescent	48
3.7	The supraspinatus tendon (SS) and the infraspinatus (IS)	50
3.8	The three facets on the greater tuberosity	51

LIST OF FIGURES

3.9	(i) The anterior margin of the greater tuberosity (ii) The superior margin of the “sulcus”	51
3.10	The relationship between the supraspinatus (SS) and infraspinatus (IS) tendons and the anatomic landmarks	52
3.11	Specimen with intervals between tendons marked sharply with methylene blue. Supraspinatus (SS); Infraspinatus (IS), Teres Minor (TM)	53
3.12	Specimen with soft tissues removed, periphery of rotator cuff insertions marked at 3-mm intervals	54
3.13	Sample plots of 4 trials mapping points around the subscapularis	54
3.14	(a) Normal supraspinatus tendon at the articular cartilage margin as viewed from the right glenohumeral joint through a posterior arthroscopic portal. (b) Debrided footprint of a right partial-thickness articular-sided rotator cuff tear with exposed bone lateral to articular margin	56
3.15	(i) Lateral view of intact cuff tendons with intervals marked before dissection. (ii) Footprints of the supraspinatus	57
3.16	Location of strain gauges	59
3.17	Measurement of strain using DVRTs	60
3.18	Experiment setup for MRI intratendinous strain testing	61
3.19	Representative MRI at 15° of glenohumeral abduction demonstrating the superior (S), middle (M), and inferior (I) regions of the supraspinatus tendon	62
3.20	Specimen mounted on testing rig at 0° of abduction	64
3.21	Schematic of the test configuration for the multiple strain measurement system	66

LIST OF FIGURES

3.22	Locations of the nine markers placed on the articular surface of the supraspinatus tendon	67
3.23	Aluminium clamp	73
3.24	Freeze clamp technique	74
3.25	Suture technique	74
3.26	Mean loads to failure of various clamps	75
3.27	Modulus of elasticity of the supraspinatus tendon	76
3.28	Mean elastic modulus values and standard deviations of the infraspinatus and teres minor tendon in hanging arm position, in 60° of glenohumeral abduction and the average of both values	77
3.29	Distortional strain distribution in model with subacromial impingement at humeroscapular angles of 0°, 30° and 60°	79
3.30	The anatomic areas of different material properties	81
3.31	Quadrangular meshes of the model	81
3.32	Loading condition of the model	81
3.33	Tensile stress at abduction angles of 0° (A), 30° (B) and 60° (C)	83
3.34	Compressive stress at abduction angles of 0° (A), 30° (B) and 60° (C)	84
3.35	Overall geometry of each type of partial-thickness tear model at 0° abduction: articular-side tear (A), bursal-side tear (B), and intratendinous tear (C)	85
3.36	Stress distribution in articular-side tear models at 0° abduction: von Mises stress (A) and maximum principal stress (B)	86

LIST OF FIGURES

3.37	Stress distribution in bursal-side tear models at 0° abduction: von Mises stress (A) and maximum principal stress (B)	86
3.38	Stress distribution in intratendinous tear models at 0° abduction: von Mises stress (A) and maximum principal stress (B)	87
3.39	Stress distribution in articular-side tear models at 60° abduction: von Mises stress (A) and maximum principal stress (B)	87
3.40	Stress distribution in bursal-side tear models at 60° abduction: von Mises stress (A) and maximum principal stress (B)	87
3.41	Stress distribution in intratendinous tear models at 60° abduction: von Mises stress (A) and maximum principal stress (B)	88
3.42	Oblique coronal section of the hexahedral meshes of the model	90
3.43	Maximum principal stress in the sagittal plane through the (a) anterior edge, (b) middle section, and (c) posterior section of the supraspinatus tendon.	91
4.1	Schematic diagram of Hatakeyama's customised shoulder positioner	94
4.2	Purpose-built rig	95
4.3	Initial incision for skin removal	97
4.4	Supraspinatus and subscapularis	98
4.5	Infraspinatus and teres minor	98
4.6	Clipped acromium and coracoid process	99
4.7	Direction of axes	102
4.8	Three-dimensional diagram with forces on the glenohumeral joint	102
4.9	Whip stitches	105

LIST OF FIGURES

4.10	Mounting of shoulder specimen with humerus at reference position	107
4.11	Schematic diagram of a DVRT	108
4.12	Procedure to insert DVRT at anterior of the articular side of supraspinatus	110
4.13	Positions of DVRTs (plan view)	111
4.14	Plan view of planes used in experiment	112
4.15	Position and width of simulated tear	114
4.16	Anchors positions on the humeral head	115
4.17	(a) Single-row repair (b) Double-row repair	115
4.18	Various regions of the rotator cuff	117
4.19	Anatomical position of rotator cuff	118
4.20	i) Solid and melted dental wax; ii) Clay moulding	119
4.21	Print screen of the software “Digimizer”	121
4.22	Traces and dimensions of the delineated footprint for a shoulder specimen	122
4.23	Purpose-built serrated jaw clamp	124
4.24	Rotator cuff tendons	125
4.25	Tendons sutured with wire mesh	125
4.26	Tensile test setup	126
4.27	Flowchart for the FEA of the rotator cuff	128
4.28	MRI of an anterior view of a right shoulder	129
4.29	Flowchart of the general steps in MIMICS	130
4.30	Segmented mask of the humeral head created through thresholding	130
4.31	Mask segmentation	131
4.32	Point cloud parts of humeral head and tendons	132

LIST OF FIGURES

4.33	Overview of the ScanTo3D Process	132
4.34	Volume rendering of the solid model	133
4.35	Assembly of the sectioned rotator cuff tendons	135
4.36	FE model of rotator cuff tendons	136
4.37	Nodes constrained in the z-direction at the centre of each tendon region	139
4.38	Loading conditions of the rotator cuff tendons	140
4.39	Nodes chosen to calculate strain at each tendon region	141
5.1	Effect of elevation angle on the supraspinatus strain at various positions in the scapular plane	142
5.2	Effect of elevation angle on the strain of posterior rotator cuff tendons in the scapular plane	143
5.3	Effect of elevation angle on the strain of rotator cuff tendons in the sagittal plane	144
5.4	Effect of elevation angle on the strain of rotator cuff tendons in the coronal plane	144
5.5	Effect of rotation angle on the strain of the rotator cuff tendons in neutral position	145
5.6	Effect of anterior 2mm partial tear on SSar-ant strain	146
5.7	Effect of anterior 2mm partial tear on SSbur-ant strain	147
5.8	Effect of anterior 2mm partial tear and full tear on SSbur-pos strain	147
5.9	Effect of repair on SSar-ant strain	148
5.10	Effect of repair on SSbur strain	148

LIST OF FIGURES

5.11	Mean area obtained from the various methods for the respective tendon (n=4)	151
5.12	Maximum principal stress of the rotator cuff tendons from 0° to 60°	154
5.13	Maximum principal stress of the rotator cuff tendons at 0°	155
5.14	Maximum tensile stress of the supraspinatus at 0°	156
5.15	Rotator cuff tendons at elevation angle of 60°	156
5.16	Maximum principal stress of the rotator cuff tendons at 60°	157
5.17	Comparison of results between experiment and FE for SSar-ant	158
5.18	Comparison of results between experiment and FE for SSbur-ant	158
5.19	Comparison of results between experiment and FE for SSbur-pos	159
5.20	Comparison of results between experiment and FE for IS	159
5.21	Comparison of results between experiment and FE for SC	160
5.22	FE strain profile across anterior supraspinatus at elevation angle of 60°	160
6.1	Strain profile across anterior supraspinatus at elevation angle of 60°	162
6.2	Tensile and compressive strains within the tendons during internal rotation from plan view of the humeral head	163
6.3	Strain redistributed due to tear at anterior SS	164
6.4	Sutures at the single-row repairs	164
6.5	Sutures at the double-row repairs	165
6.6	Shear stresses across the longitudinal section of the supraspinatus	173

LIST OF TABLES

List of Tables

3.1	Cross sectional area measurement methods	71
3.2	Material properties of anatomic components	80
3.3	Maximum von Mises stress at tendon insertion in partial-thickness tear models (percent of intact tendon models)	86
4.1	Muscle segments and coordinates	101
4.2	Calculated load for each muscle segment	104
4.3	Distance between barbs (in mm)	109
4.4	Test configurations	113
4.5	Maximum length and width of the footprint as per its anatomic orientation	122
4.6	Types and number of elements and nodes used in FE model	137
4.7	Material properties assigned to each part	138
4.8	Load applied to each rotator cuff tendon	140
5.1	Width and thickness of the tendons (n = 19)	149
5.2	Length of the tendons (n = 19)	150
5.3	Dimensions and surface area of the footprint (n = 8)	152
5.4	Elastic moduli of the rotator cuff tendons	153
6.1	Comparison of thickness and width of tendons between current and past studies	167

LIST OF TABLES

6.2	Comparison of length of tendons between current and past studies	167
6.3	Comparison of footprint dimensions between current and past studies	168
6.4	Comparison of footprint surface areas between current and past studies	169
6.5	Comparison of elastic moduli between current and past studies	171

1 INTRODUCTION

1.1 Background

An increasing number of middle-aged and elderly patients are seen and operated on, for rotator cuff tears of the shoulder joint in Singapore [1-2]. There are clinical studies [3-7] and cadaver studies [8-11] that describe the patho-physiology of cuff tears, yet few have attempted to develop a model to predict patterns of cuff tears. Finite element (FE) models that had been developed were solely concentrated on the supraspinatus tendon tears, and only at different angles of abduction [12-14]. According to the author's knowledge, no two or three dimensional FE modeling and analysis has been performed on the rest of the rotator cuffs and none has been done on shoulder positions relating to daily activities, such as lifting, hair combing and throwing. These are common overhead activities used in daily life that will require the use of the rotator cuffs.

At present, there is a lack of anthropometrical data on Asian shoulder rotator cuff tendons and of their insertion sites. Thus, in this study, an anatomical study of the rotator cuff tendons and their insertion sites would be carried out. Simultaneous strain measurements of the various rotator cuff tendons would also be done. A finite element model would be created to simulate the strains at higher loads which could not be carried out during cadaveric studies. With that, the author hopes that the results can aid orthopaedic surgeons to optimise surgical treatment techniques, prevent propagation of tears and improve rehabilitation.

1.2 Objective and scope

The objective of this project is to investigate the effect of glenohumeral positions, tear propagation and surgical repair techniques on the strain profile of the rotator cuff tendons.

The objective of the research would be achieved with the following project scope:

- 1) An anthropometric study and characterisation of Asian rotator cuff tendons.
 - In general, Asians are physically smaller than Caucasians and detailed anthropometric data on the rotator cuff tendons are lacking. The results from this phase of work will provide useful information for surgeons and the current project.
 - Material properties of the tendons will be investigated by tensile tests. The material properties will be used for the finite element analysis.
- 2) An in vitro strain study of rotator cuff tendons at various glenohumeral positions due to simulated tear configurations and surgical repair techniques.
 - Experiments will be carried out with the glenohumeral joint and the entire rotator cuff intact. Simultaneous strain readings of the supraspinatus at both the articular and bursal side, and infraspinatus and teres minor at the bursal side will be recorded. Results from the experiments will be used to investigate how the various tendons interact at different positions, tears and repairs.
 - The results can be used by surgeons and physiotherapists for recommendation of suitable surgical treatment and rehabilitation.

- 3) Development of a three-dimensional finite element (FE) model to predict strains at different positions.
 - A validated FE analysis allows the simulation of high physiological loads which are not feasible during experiments. This would provide a comprehensive biomechanical model of the rotator cuff tendons as a whole.

1.3 Contributions

The clinical contribution of this research is to quantitatively determine the effect of supraspinatus tendon tears and repair on the strain of supraspinatus tendon itself and the remaining intact infraspinatus and subscapularis tendons. This is to assist orthopaedic surgeons and physiotherapist clinically in providing the appropriate surgical treatment and suitable rehabilitation for patients with rotator cuff tendon tears.

Furthermore, the lack of anthropometric data of the Asian population motivated the collection of anatomical and strain data in the current research. This data from the Asian population, which is in general physically smaller than the Caucasian population, would provide more relevant information of Asian patients for surgeons and researchers.

The development of a three-dimensional finite element model which includes the neighbouring cuff tendons, infraspinatus and subscapularis, instead of solely on the supraspinatus itself, would provide a comprehensive biomechanical model and analysis of the rotator cuff tendons as a whole.

1.4 Experimental Hypotheses

Based on previous biomechanical and histological reports [9-11, 15-19] , the following hypotheses were made:

- 1) Rotator cuff tendon strains vary with glenohumeral elevation and rotation in the different planes.
- 2) For supraspinatus tendons subjected to tensile loading, there exists a strain gradient (difference) between the articular and bursal side of the tendon.
- 3) Simulated tears created at the anterior supraspinatus tendon increase the strains at the posterior.

1.5 Organisation of Report

The organisation of this report is structured as follows:

Chapter 1 provides the background to the motivation of this research. The objective and scope of this project are stated here.

Chapter 2 presents the anatomy of the shoulder complex and the rotator cuff.

Chapter 3 covers the detailed literature review on the anatomy, strain studies and FE models researched on the rotator cuff.

Chapter 4 describes the methodology of the experiments and finite element analysis.

Chapter 5 provides the results of the work described in Chapter 4.

Chapter 6 discusses on the results documented in Chapter 5.

Chapter 7 provides the conclusions and future work of the study.

2 SHOULDER COMPLEX

2.1 General anatomy of the shoulder complex

The shoulder complex comprises of a series of joints, muscles, ligaments, bursae and capsules. There is an intricate relation between the bone structures and their surrounding soft tissues. The three main bones related to the shoulder joints are the scapula, the clavicle and the humerus (Figure 2.1).

Figure 2.1: Bones of the shoulder [20]

Ligaments connect the bones of the shoulder, and tendons join the bones to surrounding muscles. The biceps tendon attaches the biceps muscle to the shoulder and helps to stabilize the joint. Four short muscles originate on the scapula and pass around the shoulder where their tendons fuse together to form the rotator cuff [21].

Moving together, the four shoulder joints allow unimpeded and smooth motion of the arm. The anatomical joints (Figure 2.2) comprise of the glenohumeral joint, the

acromioclavicular joint and the sternoclavicular joint while the physiological joint includes the scapulothoracic joint. The glenohumeral joint is the articulation between the humeral head and the glenoid fossa of the scapula. The acromioclavicular joint is where the clavicle meets the acromion. The sternoclavicular joint serves as the only structural attachment of the clavicle, scapula, and upper extremity to the axial skeleton. The scapulothoracic joint is a ‘false’ joint where the scapula glides against the thorax. The glenohumeral joint is the core of motion at the shoulder complex with the acromioclavicular joint and the sternoclavicular joint broadening the range of movement [22]. Thus the shoulder joint has the greatest range of motions in the human body.

Figure 2.2: Shoulder joints [23]

2.2 Glenohumeral joint

The glenohumeral joint is a multiaxial ball-and-socket joint lying between the pear-shaped glenoid fossa of the scapula (1/4 size of humeral head) and the hemispheric humeral head. The joint cavity is cushioned by articular cartilage covering the head of the humerus and face of the glenoid. The joint is stabilized by the labrum, a ring of fibrous cartilage surrounding the glenoid. Due to its design for maximum mobility, it is prone to instability. As the large humeral head articulates with a relatively small and shallow glenoid surface, and also due to the relative laxity of the joint capsule, there is an inclination for the humeral head to be displaced from the glenoid surface during active shoulder movements [24-25].

The tissues surrounding the glenohumeral joint are grouped into four separate layers, alternating between muscular and fibrous elements [26]. As shown in Figure 2.3, layer I, the most superficial level, consists of the pectoralis major and deltoid muscles. Layer II is a continuous fascial layer that spread circumferentially from anterior to posterior and incorporates the clavipectoral and posterior scapular fascia. Layer III includes the musculotendinous rotator cuff and layer IV, the deepest level, involves the fibrous capsular components.

Figure 2.3: Supporting layers of the glenohumeral joint [26]

2.3 Rotator cuff

2.3.1 Dynamic stabilization

The opposing requirements on the shoulder complex for both mobility and stability are met through active forces or dynamic stabilization. Basically, dynamic stability exists when passive forces such as articular surface configuration, capsule, or ligaments do not play an important role in limiting a moving segment or set of segments. Instead, it relies greatly on active forces or dynamic muscular control. Dynamic stabilization results in a large range of mobility for the shoulder complex and offers sufficient stability when the complex is functioning normally.

Muscles surrounding the shoulder have a crucial role in the extensive mobility displayed by the glenohumeral joint. Although there are 26 groups of muscle controlling the shoulder girdle itself, the rotator cuff is believed to be the main dynamic stabilizer of the glenohumeral joint [27]. It has been shown from electromyographic studies that all four muscles of the rotator cuff are active during joint movement but with varying force [28]. It acts as a functioning unit of four muscles keeping the humeral centre within the glenoid during active arm elevation. This is done so by creating tension in the glenohumeral joint muscles, compressing the humeral head into the glenoid fossa [29].

2.3.2 Gross anatomy and function of rotator cuff

The four rotator cuff muscles are supraspinatus (SS), infraspinatus (IS), teres minor (TM) and subscapularis (SC) (Figure 2.4). They originate from the body of the scapula

and wrap around the humeral head as they insert along the tuberosities of the proximal humerus. The subscapularis muscle makes up the anterior portion of the rotator cuff. Its origin is along the costal surface of the scapula and its insertion is at the less tuberosity of the humerus [30]. It mainly acts as an internal rotator but also contributes as an arm abductor and humeral head depressor. Posteriorly, the infraspinatus and teres minor muscles originate from the infraspinatus fossa and dorsolateral border of the scapula, respectively, and insert onto the greater tuberosity of the humerus. These muscles rotate the humerus externally and, together with the subscapularis and supraspinatus muscles, stabilize the glenohumeral joint. The supraspinatus muscle takes its origin from the suprascapular fossa and inserts along the greater tuberosity of the humerus. It compresses the humerus to the glenoid during active shoulder motions and assists the deltoid in effecting humeral abduction [31]. The space between the subscapularis and supraspinatus tendons is known as the rotator interval.

Figure 2.4: Muscles of the rotator cuff [32]

2.4 Anatomical position and movement of the shoulder complex

2.4.1 Definition of the anatomical position

The anatomical planes and terms are defined such that the person is standing erect, upper limbs hang loosely by the sides with the palm of the hand facing forward (Figure 2.5). This is called the anatomical position. Imaginary reference planes passing through the body facilitate the understanding of how one structure may relate with another and the movement of one segment with respect to another.

The sagittal (median) plane passes through the body from front to back and divides it into two symmetrical right and left halves. Any plane parallel to this is also known as a sagittal (paramedian) plane. A structure nearer to the median plane compared to another is medial to the other. If it is further away from the median plane, it is lateral to the other. Coronal planes are vertical planes perpendicular to the median plane. Transverse planes are at right angles to both the median and coronal planes. The terms anterior and posterior refer to the front and back of the body respectively. Superior and inferior refers to above and below respectively, with reference to another structure [33].

Figure 2.5: The anatomical position showing the cardinal planes and directional terminology [33]

2.4.2 Resting position of the scapula

The scapula rests at a position on the posterior thorax approximately 25 mm from the sagittal (median) plane, between the second and the seventh ribs. The scapula is internally rotated 30° to 45° from the coronal plane (Figure 2.6A) and is tipped anteriorly around 10° to 20° from the vertical (Figure 2.6B). From the posterior view, the longitudinal axis of the scapula (90° to an axis through the spine) is upwardly rotated 10° to 20° from vertical (Figure 2.6C) [34].

Figure 2.6: The resting position of the scapula on the thorax [35]

2.4.3 Movement of glenohumeral joint

For descriptive purposes, the movements of which the shoulder joint is capable are flexion and extension, abduction and adduction, and medial and lateral rotation. As the plane of scapula is different from the cardinal planes of the body, the axes about which the movements occur have to be carefully defined.

Figure 2.7 defines two sets of axes, one with respect to the cardinal planes of the body, and the other with respect to the plane of scapula, which is inclined approximately 45° to both the coronal and sagittal planes. In this report, the movements are defined with reference to the plane of scapula unless otherwise stated [33].

Figure 2.7: Axes of movement at the shoulder joint: (a) with respect to the cardinal axes of the body; (b) with respect to the plane of scapula [33]

Flexion and extension occur about an axis perpendicular to the plane of the scapula (Figure 2.8a), so that in flexion the arm moves forwards and medially at an angle of approximately 45° to the sagittal plane. In extension it is moved backwards and laterally. The range of flexion is approximately 110° and that of extension 70° . Movements of the shoulder girdle may extend both of these ranges such that flexion of the upper limb with reference to the trunk reaches 180° and extension slightly exceeds 90° .

Abduction and adduction occur about an oblique horizontal axis in the same plane as the scapula. In abduction the arm moves anterolaterally away from the trunk (Figure

2.8b). The total range of movement at the glenohumeral joint is 120° , however only the first 25° occurs without concomitant rotation of the scapula. Between 30° and 180° , scapula rotation enhances shoulder abduction in the ratio of 1:2. This is known as scapulohumeral rhythm.

Rotation occurs about the longitudinal axis through the humerus. In lateral rotation, it is the anterior surface of the humerus which is turned laterally (Figure 2.8c). It has a maximum range of 80° . Medial rotation causes the anterior surface of the humerus to turn medially. The maximum range of medial rotation exceeds 90° .

Figure 2.8: Movements at the shoulder joint with respect to the plane of the glenoid fossa [33]

2.4.4 The Scapulohumeral rhythm

The scapula on the thorax contributes to flexion and abduction of the humerus by upwardly rotating the glenoid fossa 50° to 60° from its resting position [36]. Several investigators have attempted to relate glenohumeral and scapulothoracic motion during arm elevation in various planes [37-41]. The overall ratio of 2° of glenohumeral to 1° of

scapulothoracic motion during arm elevation studied by Inman's group [37] is commonly used, and the combination of concomitant glenohumeral and scapulothoracic motion most commonly referred to as scapulohumeral rhythm. According to the 2-to-1 ratio framework, flexion or abduction of 90° in relation to the thorax would be accomplished through approximately 60° of glenohumeral and 30° of scapulothoracic motion.

3 LITERATURE REVIEW

3.1 Gross anatomy of rotator cuff

An understanding of normal rotator cuff anatomy is important for the surgeon treating rotator cuff abnormalities. Knowledge of the gross and histologic appearances of the cuff provides relevant insight into the abnormal state as well as a foundation for reconstructing the anatomy of the diseased rotator cuff. In 1992, Clark and Harryman [42] carried out gross anatomic and histologic studies on cadaveric specimens to delineate the relation between the rotator cuff tendons and their underlying capsular elements. It was described that the rotator cuff is made up of multiple, confluent tissue layers functioning in unison. The tendinous insertions of the rotator cuff, the articular capsule, the coracohumeral ligament and the glenohumeral ligament interweave and merge, forming a common insertion on the humerus tuberosities. Figure 3.1 shows the complete myotendinous cuff and capsule spread out after they were removed from the humeral head and scapula and were incised through the axillary pouch. The structures shown are the subscapularis (SC), the osteomized coracoid process (C) with the attached coracohumeral ligament (chl), the supraspinatus (SS), the infraspinatus (IS), and the teres minor (TM).

Figure 3.1: Complete myotendinous cuff and capsule spread out after removal from scapula and humeral head [42]

Figure 3.2(i) shows the lateral portion of the proximal humerus end and the outer portion of the attached cuff muscles, which have been removed from each other and dissected off the capsule, with their insertions on the humerus left intact. The supraspinatus (SS) and infraspinatus (IS) tendons fuse about 15 mm proximal to their insertion sites and cannot be split by blunt dissection. The individually separated muscles of teres minor and infraspinatus join near their musculotendinous junctions. The teres minor and the subscapularis muscles are inserted on the humerus surgical neck, and extend about 20 mm inferiorly where their tendons attached onto the tuberosities.

Figure 3.2(ii) is the schematic diagram of the specimen shown in Figure 3.2(i), illustrating the relationships of the subscapularis (SC), biceps (B), supraspinatus (SS)

and infraspinatus (IS) tendons and of the bicipital groove (BG) at the level of the insertion of the cuff on the greater (GT) and lesser (LT) tuberosities.

At the proximal end of the bicipital groove, the supraspinatus and subscapularis tendons merge to sheath around the biceps tendon. A segment of supraspinatus tendon forms the roof of this sheath while the superior section of the subscapularis tendon forms its floor. Figure 3.2(iii) is a diagrammatic representation of Figure 3.2(i) and (ii) showing the normal interweaving of the fibers from the subscapularis (SC), supraspinatus (SS) and infraspinatus (IS) tendons in the region of the rotator cuff. The fibers from the subscapularis tendons form the floor of the sheath of the biceps tendon (BT) within the bicipital grooves (BG). The frequent detection of subscapularis tendon tears with lesions of the long head of biceps showed that this link is both clinically and statistically important [43].

Figure 3.2: Dissection of cuff tendons, showing how the tendons converge as they insert on the humerus [42]

3.2 Histology of rotator cuff

Five distinct layers are identified through histologic sections of the supraspinatus (SS) and infraspinatus (IS) [42] (Figure 3.3). These layers also receive strengthening from the coracohumeral ligament (chl) and are adjacent with the glenohumeral capsule. At the surface, Layer 1 has a thickness of 1 mm and comprises large arterioles. It is made up of coracohumeral ligament fibres, aligned obliquely to the axis of each muscle. Layer 2 is 3 to 5 mm thick, comprises of large bundles (1 to 2 mm in diameter) of tightly packed, parallel tendon fibres, which directly insert into the humerus head. Layer 3 is about 3 mm thick and, compared to layer 2, it has smaller and more loosely packed tendinous bundles. Fibres within this layer crossed one another at 45 degrees and intermingle with the fibres of the adjacent infraspinatus and subscapularis tendons. Blood vessels present in this layer are smaller than in layers 1 and 2. Layer 4 composes loose connective tissue of thick collagen bands that blend with the coracohumeral ligament along the anterior margin of the supraspinatus. Layer 5 is a 2-mm thick joint capsule, comprises of a sheet of intertwined collagen fibrils which extends from the glenoid labrum to the neck of the humerus.

Figure 3.3: Schematic diagram of a rotator cuff dissection through the supraspinatus (SS) and infraspinatus (IS) to demonstrate the 5-layer histologic configuration of the cuff [42]

This structural architecture may enhance the rotator cuff's resistance to failure with repeated loads, for tension generated in any single musculoskeletal unit could be expected to result in a distribution of forces over an expanded area. Moreover, in circumstances under which the rotator cuff does fail, the network of interdigitating fibres contributes to the tissue's structural integrity, affording retention of sutures during operative repair. This layered anatomy of the rotator cuff also gives us a better perception of the pathology of different kinds of partial-thickness tears, especially the intratendinous type [42].

3.3 Classification of rotator cuff tears

A full-thickness rotator cuff tear is defined as one that extends from the articular side to the bursal side of the cuff, resulting in direct communication between the subdeltoid bursa and the joint cavity. In comparison, partial-thickness tears do not involve the whole thickness of the cuff (Figure 3.4). They only involve one surface of the cuff, either the articular-side (inferior surface) or the bursal side (superior surface). Intratendinous tear is a special type of partial-thickness tear that involves only the midsubstance of the cuff [44].

Figure 3.4: Classification of partial tears by location. **A:** Articular surface partial tear; **B:** bursal surface partial tear; **C:** intratendinous partial tear [45]

Ellman [46] had classified partial tears by their depth (Figure 3.5): grade 1 tears have depth up to 3 mm and involved only the capsule or superficial fibres are involved; grade 2 tears have depth between 3 and 6 mm and involved less than 50% of the cuff thickness; and grade 3 tears have depth of more than 6 mm, and involved more than 50% of the cuff thickness.

Figure 3.5: Classification of partial tears by depth [45]

3.4 Incidence and prevalence of rotator cuff tears

The true incidence of partial-thickness rotator cuff tears is still unknown. In the early 1930s, Codman [3] noted that the incidence of partial-thickness tears was possibly twice of full-thickness tears. Most of the current data have been obtained from cadaveric studies that are skewed to the older population. However, the true incidence of partial-thickness tears in young overhead-throwing athletes is not known. A large proportion of these tears occurs in the supraspinatus tendon.

Yamanaka and Fukuda [47] reported an incidence of partial-thickness tears of 13% and full-thickness tears of 7% in a group of 249 cadaveric specimens. Partial tears were further grouped as bursal-sided (2.4%), intratendinous (7.2%) and articular-sided (3.6%), showing that intratendinous tears to be more common compared to bursal-sided and articular-sided tears. Data on the incidence of rotator cuff tears in living patients are more difficult to obtain. The incidence of rotator cuff tears also increases with increasing age as the strength of human tendons decreases with older individuals [48]. It is clinically observed that articular-sided tears are two to three times more common than bursal-sided tears [49].

Payne et al. [50] verified that articular-sided tears composed 91% of all partial-thickness tears among a young athlete population. In a study by Sher et al. [51], out of 100 asymptomatic volunteers who underwent MRI examination, 22% of patients had partial thickness tears and 14% had full-thickness tears. The incidence of rotator cuff tears increased with age. Partial tears were uncommon in those under 40 (4%), and full-

thickness tears hardly present in individuals under 60 years old. As shown by these figures, partial thickness tears are not rare in the elderly and can be asymptomatic. If proper treatment is not given, these partial tears are likely to propagate to full-thickness tears and may be disabling.

3.5 Pathophysiology

There is still a debate concerning the pathogenesis of rotator cuff tears. A variety of different factors are felt to be important in the etiology of partial thickness rotator cuff tears. These factors can be generally classified as either extrinsic or intrinsic to the rotator cuff tendons [7]. Extrinsic causes may be due to either subacromial impingement [52], anterior shoulder instability [53], internal impingement [54-56], a single acute traumatic injury or repetitive microtrauma [57]. Intrinsic factors include age-linked metabolic and vascular transformations that lead to degenerative tearing [58] or intratendinous lesions developing from shear stress [59]. Very often, the development of partial thickness tears may be the resultant of more than one of these factors [7, 60-61].

It is crucial to find out the underlying cause of the different partial thickness tears types to determine the suitable surgical procedures and it may also allow insight into the healing potential of the tears [4-5, 7, 62]. The extrinsic theory of rotator cuff pathophysiology was popularised by Neer [6] in 1972. He demonstrated that when the shoulder elevates, the rotator cuff and surrounding soft-tissues impinge in the space beneath the coracoacromial arch, which is defined by the acromion superiorly, the coracoacromial ligament superomedially and the coracoid process anteriorly. Progressively, this impingement may result in a spectrum of rotator cuff tendinopathy. With this impingement theory, he introduced a combined procedure of cuff repair and anterior acromioplasty and achieved good results. A finite element analysis of the supraspinatus tendon has shown that subacromial impingement creates extrinsic compression and stress concentrations adequate to cause tearing on bursal, articular

sides as well as within the tendon [63]. Although this data suggested that subacromial impingement may cause any of the partial thickness tear, cadaveric [8] and clinical [64] studies have demonstrated that bursal-sided tears are more frequently associated with subacromial impingement.

Age-linked degenerative changes, including decreased cellularity, fascicular thinning and disruption, accumulation of granulation tissue, and dystrophic calcification, have all been observed and are unlikely to be reversible. At the articular surface of the rotator cuff lateral to the rotator cable (Figure 3.6) [65], a zone of relative hypovascularity [42, 66-67] is seen especially in older patients [68-69], with thinner and less homogeneously aligned collagen bundles. Moreover, the ultimate stress to failure of the rotator cuff at the articular side is approximately half of that at the bursal side [5]. Both clinical and cadaveric studies [51, 58, 70] have shown that articular side tears are mainly associated with intrinsic pathologic changes of the rotator cuff and its prevalence increases with age.

Figure 3.6: Superior and posterior projections of the rotator cable and crescent. The rotator cable extends from the biceps to the inferior margin of infraspinatus, spanning the supraspinatus and infraspinatus insertions. C, width of rotator cable; B, mediolateral diameter of rotator crescent; S, supraspinatus; I, infraspinatus; TM, teres minor; BT, biceps tendon [65].

Another probable cause of partial-thickness tears and their propagation may be differential shear stress within the tendons. The 5-layer histologic structure of the rotator cuff shed light on the potential development of internal shear forces within the cuff [42]. Nakajima et al. [59] found that the histological and biomechanical properties of the bursal and articular tendon layers were different. The bursal layers, composed primarily of tendon bundles, elongate to a tensile load, and are resistant to rupture, whilst the articular layers, a complex of tendon, ligament and joint capsule, are unstretchable and tear easily. They suggest that intratendinous tear is caused by the shear within the supraspinatus tendon. Intratendinous tears were commonly associated with approximately bursal tears and articular tears [5, 47]. Through these findings, an

increasing attention on intratendinous strain and its relation with intratendinous tear have increased the understanding of the causes and optimal treatment of partial thickness tears [4, 7].

Intratendinous strain as a contributing factor in the development and propagation of partial-thickness tears is particularly significant in overhead throwing athletes, as their rotator cuff tendons are often under repetitive strains with powerful eccentric forces acting on the tendon during deceleration. Repetitive microtrauma from intratendinous strain taking place during eccentric contraction of the rotator cuff in the deceleration phase of throwing together with subtle capsular laxity and internal impingement are probable prominent factors in the pathogenesis of articular-sided partial-thickness tears often seen in overhead throwing athletes [57, 71]. Studies done on the intratendinous strain and tears will be further discussed in detail in section 3.7.2.

3.6 Footprint and dimensional measurement of rotator cuff

For appropriate diagnosis and treatment of partial thickness tears, it is important to understand the normal anatomy of the rotator cuff, in particular its attachment to the humeral head. In respect to surgery, this information allows the tendons to be restored to their original anatomic positions, hence, optimising the potential outcomes. Although Clark and Harryman [42] gave a detailed analysis of the entire rotator cuff insertion, apart from thickness, they did not quantify any dimensions of the insertion.

In 1998, Minagawa et al. [72] were the foremost to delineate the insertions of the supraspinatus and infraspinatus (Figure 3.7) and reference them to the three facets of the greater tuberosity (Figure 3.8).

Figure 3.7: The supraspinatus tendon (SS) and the infraspinatus (IS) [72]

Figure 3.8: The three facets on the greater tuberosity: superior facet (S), middle facet (M), and inferior facet (I) [72]

The cuff tendon attachments to the facets were examined, and the location of attachment was measured with respect to the anterior margin of the greater tuberosity and the superior margin of the sulcus (anatomic neck without cartilage) (Figure 3.9).

Figure 3.9: (i) The anterior margin of the greater tuberosity. (ii) The superior margin of the “sulcus” [72].

The anterior of the cuff tendon, approximately 12.6 mm from the anterior margin of the greater tuberosity, was composed of only supraspinatus tendon, while the middle portion, approximately 9.8 mm in width, was composed of both the supraspinatus and infraspinatus tendons, and the most posterior part, approximately 12.9 mm in width, was composed of only the infraspinatus tendon (Figure 3.10).

Figure 3.10: The relationship between the supraspinatus (SS) and infraspinatus (IS) tendons and the anatomic landmarks. (a) Anterior margin of the greater tuberosity; (b) Anterior margin of the IS tendon; (c) Posterior margin of the SS; (d) Superior margin of the sulcus; (e) Posterior margin of the IS tendon [72].

However, in their study, Minagawa et al. [72] concentrated solely on the length and overlap of the supraspinatus and infraspinatus tendons as a guide for surgical treatment without quantifying the width of the insertion.

In the following year, Tierney et al. [73] verified a standard, measurable pattern on the insertional anatomy and termed it the footprint of the rotator cuff.

In 2002, Dugas et al.[74] employed a 3-space digitizer to map the footprint of 20 normal cadaveric rotator cuff specimens of all four tendons. The interval between the supraspinatus and infraspinatus muscle bellies and the interval between the infraspinatus and teres minor muscle bellies were dissected bluntly after all other soft tissues were removed. With the tendons still under tension, the blade was dipped in methylene blue and the incision in the tendon was marked (Figure 3.11).

Figure 3.11: Specimen with intervals between tendons marked sharply with methylene blue. Supraspinatus (SS); Infraspinatus (IS), Teres Minor (TM) [74]

The muscles and tendons of the rotator cuff were then incised near their insertions onto the humerus. Following that, the margin of the insertion onto the greater tuberosity was marked at 3-mm intervals with an ultra-fine tipped permanent marker (Figure 3.12). Using a digitiser, the points that were marked on each specimen were mapped in 3 dimensions. The 3-dimensional data were reduced to 2 dimensions by projection of the points into a best-fit plane. Figure 3.13 shows the sample plots of 4 trials mapping points around the subscapularis

Figure 3.12: Specimen with soft tissues removed, periphery of rotator cuff insertions marked at 3-mm intervals [74]

Figure 3.13: Sample plots of 4 trials mapping points around the subscapularis (A), supraspinatus (B), infraspinatus (C) and teres minor (D) insertions [74]

Their values of the dimensions and surface area of the insertions and the distance from the articular surface, however, were significantly lower than other published figures [72-73, 75]. This could be due to the reduction of the 3-dimensional data into 2-dimensional space.

In 2004, with callipers, Ruotolo et al. [75] quantified the normal supraspinatus dimension at its humeral head attachment and correlated the amount of exposed bone at the footprint as an measurement of the amount of tendon loss in articular sided partial thickness rotator cuff tears.

Figure 3.14a shows a normal supraspinatus tendon at the articular cartilage margin as viewed from the right glenohumeral joint through a posterior arthroscopic portal. The “S” indicates the articular surface of the supraspinatus tendon, and the black arrows point to the normal narrow margin of exposed bone between the articular cartilage and the supraspinatus insertion. “BA” indicates the normal bare area, and “H” indicates the humeral head articular surface. Figure 3.14b shows a debrided footprint of a right partial-thickness articular-sided rotator cuff tear with exposed bone lateral to articular margin. The black arrows represent the width of exposed bone after debridement. “S” indicates the articular surface of the supraspinatus tendon; “B,” bicep tendon; and “H,” humeral articular surface

Figure 3.14: (a) Normal supraspinatus tendon at the articular cartilage margin as viewed from the right glenohumeral joint through a posterior arthroscopic portal. (b) Debrided footprint of a right partial-thickness articular-sided rotator cuff tear with exposed bone lateral to articular margin [75]

The mean anteroposterior dimension of the supraspinatus insertion was 25 mm. The mean superior to inferior tendon thickness at the rotator interval was 11.6 mm, 12.1 mm at midtendon, and 12 mm at the posterior edge. The distance from the articular cartilage margin to the bony tendon insertion was 1.5 to 1.9 mm, with a mean of 1.7 mm. Tears with more than 7 mm of exposed bone lateral to the articular margin are considered major tears approximating 50% of the tendon substance. This introduction of arthroscopic measurement of the amount of exposed footprint as a percentage of the total footprint is possibly a more objective and effective way of assessing these tears compared to merely measuring the depth of tear.

More recently in 2006, Curtis et al. [76] delineated the entire rotator cuff footprint (Figure 3.15) and referenced it to known and easily identifiable landmarks (articular surface, biceps groove, and bare area of the humerus). The subscapularis inserted on the lesser tuberosity adjacent to the biceps groove at the edge of the articular surface. It tapered away approximately 18 mm at its inferior border. The supraspinatus inserted at the articular surface along its entire insertion from the bicipital groove to the top of the bare area. The infraspinatus wrapped the posterior border of the supraspinatus superiorly at the articular surface and tapered away inferiorly, framing the bare area.

This can serve as a guide for evaluation of size, location and propagation patterns of rotator cuff tears, as well as for arthroscopic rotator cuff repair. However, they only dimensioned it using venier callipers.

Figure 3.15: (i) Lateral view of intact cuff tendons with intervals marked before dissection. (ii) Footprints of the supraspinatus (x), infraspinatus (#) and subscapularis (*) [76]

Currently, all the studies done on the footprint anatomy of the rotator cuff were on the Caucasian population. To the best of the author's knowledge, none has been done on the Asian population. Most of the studies simply use vernier callipers for dimensioning. Three-dimensional measurement of surface profile and area of the footprint using a laser digitizer with reference to the identifiable landmarks will be useful for finite element modeling.

3.7 Strain studies on rotator cuff

The following sections describe the methods and analyses of the various strain studies that have been done on the rotator cuff. The papers are presented in a chronological order.

3.7.1 Effect of arm position and repair methods on strain in repaired rotator cuff

Zuckerman et al. [77] performed a cadaveric study to determine the effect of arm position and capsular release on rotator cuff repair. All four rotator cuff muscles remained intact on the scapula in this study. Small, simulated full thickness tears were made solely in the supraspinatus. The defects were repaired in a standard way with the shoulder at 30° abduction. Strain gauges were placed on the lateral cortex of the greater tuberosity (Figure 3.16) and measurements were recorded in 36 combinations of abduction, flexion/extension, and medial lateral rotation. With small tears, tension in the repair increased considerably with movement from 30° to 15° abduction but did not vary much with rotation or flexion. Capsular release greatly reduced the force from 0° to 15° abduction.

Figure 3.16: Location of strain gauges [77]

Hatakeyama et al. [78] studied the effect of arm elevation and rotation on the strain in the repaired rotator cuff tendon. Simulated full thickness tears were created and repaired under a 3-kg tensile force with the arm in adduction. Strain on the repaired tendon was measured with differential variable reluctance transducers (DVRTs) (Figure 3.17) in 50 various arms positions, combination of elevation and medial lateral rotation in the coronal, scapular, and sagittal planes. It was observed that the strain in the sagittal plane was considerably higher than in the other planes. They concluded that the safe range of motion after repair of the rotator cuff is at elevation of 30° or more in the coronal or scapula plane with external rotation ranging from 0° to 60° .

Figure 3.17: Measurement of strain using DVRTs [78]

Hatakeyama et al. [79] further studied the effect of release of the superior capsule and the coracohumeral ligament on the strain in the repaired rotator cuff tendon. After repairing the simulated full thickness tears with the release, the strain was measured in the same manner at the various arm positions. The maximum reduction of tension in the repaired rotator cuff occurred when the arm was positioned in adduction and in 60° external rotation. Release of the coracohumeral ligament is equally as efficient as releasing the superior capsule in reducing the strain of the repaired rotator cuff.

As described above, early studies were solely concentrated on full thickness tears of the rotator cuff. It was only in recent years that partial tears received increasing attention. The following is the review on different studies on partial thickness tears relating to intratendinous strain and tears.

3.7.2 Strain studies relating to partial thickness tears on rotator cuff

Using a novel Magnetic Resonance Image (MRI) technique, Bey et al. [17] quantified intratendinous strains of supraspinatus in cadaveric shoulder specimens at various glenohumeral abduction positions in the scapular plane (Figure 3.18).

Figure 3.18: Experiment setup for MRI intratendinous strain testing [17]

The strain data were grouped into superior, middle, and inferior locations across the region where most rotator cuff tears occur clinically (Figure 3.19). Across the tendon regions, they found that the intratendinous strains varied little. However, the various abduction positions had significant effects. Intratendinous strain increased with the abduction angle. The strains at 60° were much greater than those at 15° .

Figure 3.19: Representative MRI at 15° of glenohumeral abduction demonstrating the superior (S), middle (M), and inferior (I) regions of the supraspinatus tendon. SP: supraspinatus tendon, HH: humeral head [17]

Bey et al. [11] further investigated the effect of an articular-side partial thickness rotator cuff tear on intratendinous strain fields. The cadaveric study revealed that the simulated articular-side tear led to an increase in the intratendinous strain at glenohumeral abduction of more than 15°.

The advantage of using MRI technique was that it was non-destructive and could simultaneously quantify high-resolution, intratendinous strain fields of surface and underlying tissues. However, only relatively low loads could be applied to the specimen due to the size and material limitation of the testing device. The load of 31 N used in this study was much lower than the estimated force of 120 N during maximal glenohumeral abduction [80].

Reilly et al. [10], using DVRTs, quantified the strains on the articular and bursal sides of the supraspinatus tendon with increasing load from 20 to 200 N and during 120° glenohumeral abduction with a constant tensile load of 20 and 120 N. At static load below 100 N, there is no significant difference between the articular and bursal side strains of the supraspinatus, which coincided with Bey et al.'s study [17]. However, they found that strains at the articular side increased more significantly than the bursal side of the tendon during increasing static loading of more than 100 N. At 120 N loading, during glenohumeral abduction, the difference in strain between the articular and bursal sides increased considerably. This implied that the differential strain may cause shearing between the supraspinatus tendon layers.

In the study by Reilly et al. [10], there were a couple of limitations. To measure both articular and bursal sides of the supraspinatus tendon using DVRTs, the humerus was isolated from the glenohumeral joint and all soft tissues, except the supraspinatus tendon, were removed (Figure 3.20).

Figure 3.20: Specimen mounted on testing rig at 0° of abduction. Specimen was left with the humerus and the supraspinatus [10]

To prevent impingement of the DVRTs against the articular surface during adduction of the humerus, troughs were made in the humeral head. The isolation of supraspinatus removed the interactions with other structures such as the rotator interval and the overlapping with infraspinatus. Histological data suggested that in vivo, supraspinatus loads are also transmitted through the infraspinatus and capsule [42]. It was also assumed that the line of action of the supraspinatus would stay in constant relation with the scapula, and the fixed plane of abduction of the test rig. Thus the external rotation of the humerus which accompanied terminal abduction in vivo was not modeled.

Reilly et al.[9] further determined the strain effects and propagation of supraspinatus tendon tears in cadaveric shoulders. A considerable change in strain was measured after

creating simulated tears in the supraspinatus tendon. The intratendinous tears resulted in increased strains in both the articular and bursal sides of the tendon with static loading at 0° abduction. During abduction to 120°, the bursal-side strain decreased while the articular-side increased when compared with the values for the intact tendon. These results showed that the intratendinous tears had transformed load sharing through the supraspinatus tendon. Propagation of tears and successive failure arose in abduction with a small number of joint movements. They deduced that this intratendinous tear propagation could be due to shearing forces, causing an intratendinous delamination, which subsequently caused an increased articular-sided and bursal-sided tendon strain. However, as the articular side had a lower strain to failure than the bursal side [59], a partial-thickness articular-sided tear resulted. This tear further propagated toward the bursal side during abduction, resulting ultimately in a full-thickness tear. Tendon failure was also found to occur in abduction of greater 90° with all specimens at the insertion site.

In addition, Reilly et al. [19] evaluated the relationship between passive tension of rotator cuff repairs and arm position and observed the effect of this tension on repair gap formation. They found that 30° abduction of the arm after a rotator cuff repair reduced the tension at the point of measurement by a mean of 34-N compared with that measured at 0° abduction. In cadaveric rotator cuff repairs, it was shown that the 34-N tension change, if applied statically for 24 hours, was sufficient to cause a mean gap formation of 9 mm. This insidious creep failure mechanism shows the significance of avoiding excessive tension across a sutured repair after surgery. Thus postoperative

immobilization with a 30° abduction wedge was recommended to decrease the repair tension significantly and may consequently reduce bone-tendon gap formation.

More recently, Huang et al. [81] studied the intrinsic inhomogeneous deformational characteristics of the articular and bursal sides of cadaveric supraspinatus tendons at three glenohumeral abduction angles using a novel multiple strain measuring system which simultaneously recorded surface marker displacements on two opposing soft tissue surfaces (Figure 3.21).

Figure 3.21: Schematic of the test configuration for the multiple strain measurement system [81]

Figure 3.22 shows the locations of the nine markers placed on the articular surface of the supraspinatus tendon. The markers, also placed on the bursal tendon surface, were used to compute tendon surface strains.

Figure 3.22: Locations of the nine markers placed on the articular surface of the supraspinatus tendon [81]

Under applied tensile load, the strain at the articular side was greater than the bursal side at 22° and 63° whereas at 90° , the bursal side showed greater strain. At all abduction angles, insertion strains were higher than those of the mid-tendon and tendon–muscle junction regions. The existence of inhomogeneous surface strains in the intact supraspinatus tendon, again, implied that intratendinous shear occurs within the tendon. The higher strain on the articular side of the tendon, especially at the insertion region, indicates a tendency for tears to initiate in the articular tendinous zone.

3.8 Methods for measuring surface area

The footprints of the rotator cuff tendons have irregular shapes. There is a need to find a suitable method to measure their surface areas for the experiments. Multiple techniques to measure surface area are available. Some methods include artificial substrates, area-specific sampling, geometric approximation, stone shape equations, foil wrapping, grids, stamps, wetted layer, particle layer, and planar area measurement. Suitable methods have to be chosen according to various factors such as ease of use, characteristics of the substrates and fineness of scale in measuring area. The following methods were compared using spheres of known area. They produced highly correlated measurements with regression R^2 values all greater than 0.98 and accurately estimated the surface area [82].

3.8.1 Grids

A grid system can be indicated on a substrate and the length of the gridlines measured with a map wheel or string, and a flattened projection of the substrate constructed on paper, from which the area is measured [83]. A similar procedure has been used to measure the surface area of uneven oyster shells [84]. Parallel lines, 1 cm apart, were drawn along the length of shells. The length of the lines were measured using string to follow the topography, and the area calculated using the mathematical Trapezoidal Rule [84].

3.8.2 Particle layer

This method uses an adhesive and the weight gain of a monolayer of particles. This technique is done by coating the substrates with glue or adhesive, weighing the sticky object, adding a monolayer of small plastic or glass balls, and re-weighing [85]. An equation relating the weight gain to area for objects of known area is used to convert weight to area. A modification of this procedure was developed by Bergey and Getty [82]. Instead of using an adhesive, the substrate was coated with a thin layer of petroleum jelly, which was first melted on a hotplate and then painted on with a small watercolor paintbrush. The coated object was weighed using weighing paper. Instead of small balls, table salt, which had a relatively uniform crystal size (mean=0.43 mm), was used. The salt was first sieved (sieve size=250 μm openings) to remove fines, which otherwise also coat surfaces. Petroleum jelly coated cases were rolled in a container of salt, which formed a monolayer, and were reweighed using the same sheet of weighing paper. Coating one surface of lightweight cardboard cut to different measured sizes or a series of spheres was used to regress area with the weight of the salt layer.

3.8.3 Planar area

Planar area, or the two-dimensional area enclosed by an object's perimeter, is obtained by tracing the outline of the object on paper [86] or on acetate [87], and determining the traced area by planimetry or cutting out and weighing the tracing. Alternatively, substrates can be scanned with a flatbed scanner (with a sheet of clear plastic beneath stones to protect the scanner) and the images either printed or weighed, or the area determined by image analysis (e.g., using Sigma-Scan, SYSTAT Software, Inc.,

Chicago, Illinois, to count the number of contained pixels). Simultaneous scanning of a circle or square of known area allows correction for changes in image size.

3.9 Biomechanical testing of rotator cuff tendons

Tendons transmit tensile force from muscle to the bone, hence majority of the experiments are performed in tension. Stress-Strain curves are plotted from these tests and based on those mechanical properties are determined [88].

3.9.1 Factors affecting biomechanical experiments

Experiments are designed to minimise errors or artefacts induced by undesirable factors. Usually, tensile test is done by gripping of tendons using specially designed clamps. During the experiment, the applied load and corresponding elongation of the sample are noted. Other factors affecting the mechanical properties are discussed in the following sections.

Structure of the sample

The specimen is often noted to be small by authors in various studies. Slippage is commonly reported in previous studies. Grips can be devised to minimise slippage problem but stress concentration at the region of the clamp caused premature failure of the specimens [88]. The irregular, complex geometry makes measuring cross sectional areas of these samples difficult, and measurements were reported to deviate largely. Contact and non contact approaches (Table 3.1) are being used to measure cross-sectional area of tendons. Image reconstruction techniques are also being used as a non

contact approach to estimate cross-sectional area [89]. Contact methods like use of Digital vernier callipers, micrometers and molding method were also used [90].

CONTACT METHODS	NON CONTACT METHODS
1. Digital vernier callipers 2. Pressure area micrometers 3. Thickness callipers 4. Molding methods	1. Laser micrometer 2. Laser reflectance method

Table 3.1: Cross sectional area measurement methods

Specimen orientation

Various studies had shown that the structural properties of ligaments and tendons are dependent on the loading axis with respect to their bone attachments [91-93]. Halder et al. [93] investigated the material properties of the infraspinatus and teres minor tendons from 22 fresh frozen cadaver shoulders. Significant differences between glenohumeral abduction positions were detected for the elastic modulus.

Strain rate

The tensile properties of tendons and ligaments depend on the rate at which the tendon or ligament is loaded. Most studies showed higher failure stresses and failure strains at higher strain rates but no significant differences were found in the modulus [94-97]. However, two studies have noted increases in modulus with increased strain rate. Danto

and Woo found 31% and 94% changes in the moduli of rabbit Achilles and patellar tendons over four decades of strain rate [98]. Hubbard and Soutas-Little observed a 13% change in modulus for human Palmaris longus and extensor hallucis longus tendons [99].

Temperature

In a study of pH and temperature's effect on mechanical properties, it was suggested that no change in mechanical properties was observed between 0° C and 37°C [100]. It has been reported that collagen fibres have a negative temperature-elastic modulus relationship [101]. Cyclic testing under varying temperature noted a stiffness increase with declining temperature. Hence, it is important to bring the specimen to room temperature before testing.

Hydration

Tendons contain large amounts water (60% to 80%) [102]. A study on rabbit tendons in a hydrated environment showed a greater stress relaxation [103]. Hence the specimen needs to be drip hydrated regularly.

Freezing

Samples are often frozen before being tested. Previous study has reported slight increase in stiffness [104]. In a study designed to evaluate possible changes in the mechanical properties of the rabbit medial collateral ligaments, no significant differences were found between the frozen ligaments and the fresh contralateral controls [105]. Care must be taken in preparing the tissue sample prior to freezing in order to protect the sample from dehydration. Thawing was carried out at refrigerator temperature (4°C)

overnight, and specimens were prepared for testing soon after being removed from the refrigerator.

Clamping

A study on various clamping techniques was investigated using sheep's knee joint [106]. The techniques are as follows:

- Aluminium Clamp – The muscle-tendon complex was clamped between a thin aluminium back plate and a plate with milled spikes at the contralateral side using two screws (Figure 3.23).

Figure 3.23: Aluminium clamp [106]

- Freeze Clamp - The freeze clamp has the same setup as the aluminium clamp, except for the addition of a plastic reservoir filled with solid carbon dioxide at the back plate of the aluminium clamp. The reservoir was pressed manually against the back plate until both clamp and tendon were evenly frozen to a minimum of 1 cm distal to the clamp (Figure 3.24).

Figure 3.24: Freeze clamp technique [106]

- Suture Technique – The muscle–tendon complex was wrapped taut with gauze bandage, beginning at the bony insertion. Two anti-parallel Krakow sutures were then added and knotted at the proximal end, forming a loop (Figure 3.25).

Figure 3.25: Suture technique [106]

Sixteen cadaveric knees of the sheep were tested in this study. The load to failure was estimated across the different clamping techniques (Figure 3.26). The extension hull technique and the aluminium clamp performed similarly, i.e., exceeding the computationally determined physiological forces in all but one trial and achieved higher failure loads than the suture technique. Although the freeze clamp reached the highest mean load to failure, it also failed more often than the extension hull technique.

Figure 3.26: Mean loads to failure of various clamps [106]

3.9.2 Strain studies relating to tensile testing on rotator cuff

The tensile properties of the supraspinatus tendon were investigated using 11 shoulders from fresh cadavers by Itoi et al. [107]. Each tendon was divided into three longitudinal strips: anterior, middle, and posterior. Each specimen was mounted on a tensile testing machine, with four fluorescent markers placed on both surfaces of the tendon strip. The positions of these markers were recorded during the test by two synchronized video cameras. The modulus of elasticity was significantly greater in the anterior strip ($p < 0.0001$), but there was no significant difference between the superficial and deep surfaces (Figure 3.27). It was concluded that the anterior portion of the supraspinatus tendon is mechanically stronger than the other portions, and it seems to perform the main functional role of the tendon

Figure 3.27: Modulus of elasticity of the supraspinatus tendon [107]

Halder et al. [93] investigated the infraspinatus and teres minor tendons from 22 fresh frozen cadaver shoulders. The infraspinatus tendons were divided into four strips. The tendons were held in a cryo-jaw and tested with a material-testing machine in 0° or 60° of glenohumeral abduction corresponding to 90° arm abduction. Elastic moduli were calculated (Figure 3.28). The modulus of elasticity of the midsuperior tendon strip was significantly higher than the superior and the mid-inferior moduli. The lowest modulus of elasticity was detected in the teres minor. Significant differences between glenohumeral abduction positions were detected for the elastic modulus.

Figure 3.28: Mean elastic modulus values and standard deviations of the infraspinatus and teres minor tendon in hanging arm position, in 60° of glenohumeral abduction and the average of both values [93]

3.10 Finite element analysis on rotator cuff

In 1998, a first 2-dimensional (2D) finite element (FE) model of the supraspinatus tendon at the middle section of the scapular plane was developed by Luo et al. [12] using magnetic resonance images (MRI) obtained from a fresh cadaveric shoulder. They analysed the mechanical parameters of the supraspinatus tendon at humeroscapular angles of 0° , 30° and 60° . Two acromion conditions were simulated; with and without subacromial impingement at the bursal side. The results verified that subacromial impingement led to increases in the stress and distortional strain considerably.

Figure 3.29 shows the distortional strain distribution in the model with subacromial impingement at humeroscapular angles of 0° , 30° and 60° . High distortional strain was concentrated in the critical zone of impingement from the bursal to the articular side, which spanned the thickness of the tendon. The limitation of this study was that they did not indicate the histologic differences of the tendon insertion. They also regarded the humeral head as a rigid body.

Figure 3.29: Distortional strain distribution in the model with subacromial impingement at humeroscapular angles of 0°, 30° and 60°. Insertion at articular side (a); middle portion of articular side (b); insertion at bursal side (c); impingement site (d) [12]

In 2003, Wakabayashi et al. [13] established a new 2D FE model of the normal human shoulder. The geometric shape of the model was determined by MRI of a healthy right shoulder obtained at 0°, 30°, and 60° of abduction. The model incorporated the material properties of the humeral head and those of the histologic structures (Table 3.1). Tendon insertion into the bone consists of four zones: tendon proper, noncalcified fibrocartilage, calcified fibrocartilage, and bone (Figure 3.30). These specific structures may have some influence on mechanical stress distribution. The geometric shape was composed of quadrangular meshes with finer meshes at area of higher interest (Figure 3.31). The contact area between the tendon and the humeral head was set with the contact option, and the coefficient of friction was set as 0. The distal portion of the humeral head was fixed on x and y-axes, and the tensile force was applied to the proximal end of the tendon in the direction of the x-axis (Figure 3.32). The tensile force at each angle of abduction was determined as 10 N at 0°, 53 N at 30°, and 115 N at 60°.

	Young's modulus (MPa)	Poisson's ratio
Supraspinatus tendon	168	0.497
Noncalcified fibrocartilage	572	0.432
Calcified fibrocartilage	976	0.366
Articular cartilage	35	0.450
Cancellous bone	1380	0.300
Subchondral bone	2760	0.300
Cortical bone	13800	0.300

Table 3.2: Material properties of anatomic components [13]

Figure 3.30: The anatomic areas of different material properties [13]

Figure 3.31: Quadrangular meshes of the model [13]

Figure 3.32: Loading condition of the model [13]

The tensile stress and compressive stress are shown in Figure 3.33 and 3.34 respectively. A darker colour indicates a higher stress value. In their analysis, the area of high principal stress was observed on the articular side of the supraspinatus tendon and it shifted toward the insertion as the arm was abducted. This may explain the frequent occurrence of rotator cuff tears at this site during arm elevation.

Figure 3.33: Tensile stress at abduction angles of 0° (A), 30° (B) and 60° (C) [13]

Figure 3.34: Compressive stress at abduction angles of 0° (A), 30° (B) and 60° (C) [13]

Following this research, in 2006, Sano et al. [14] studied the stress distribution in the rotator cuff tendon with three types of partial-thickness tears using 2D FE analysis. The model was developed from the intact tendon model with the same material properties and loading conditions used in the previous study [13]. Tendon defects were created on the articular surface, bursal surface and within the tendon to simulate the various partial thickness tears (Figure 3.35). Table 3.3 summarizes the comparison of the highest value of the von Mises stress in partial-thickness tears with that of the intact tendon. The von Mises stress in general increased with the presence of any type of partial-thickness tear. In all the three types of tears, a high stress concentration appeared around the articular surface at the insertion and at the site of the tear, which extended proximally (Figure 3.36-3.38). With the arm in abduction, a high stress concentration was also observed around the site of the tear (Figure 3.39-3.41). These biomechanical conditions of the supraspinatus tendon may eventually lead to a full thickness tear at the critical zone.

Figure 3.35: Overall geometry of each type of partial-thickness tear model at 0° abduction: articular-side tear (A), bursal-side tear (B), and intratendinous tear (C) [14]

	Articular side	Bursal side	Intratendinous
Abduction at 0°	98	163	125
Abduction at 60°	145	98	132

Table 3.3: Maximum value of von Mises stress at tendon insertion in partial-thickness tear models (percent of that of intact tendon models) [14]

Figure 3.36: Stress distribution in articular-side tear models at 0° abduction: von Mises stress (A) and maximum principal stress (B) [14]

Figure 3.37: Stress distribution in bursal-side tear models at 0° abduction: von Mises stress (A) and maximum principal stress (B) [14]

Figure 3.38: Stress distribution in intratendinous tear models at 0° abduction: von Mises stress (A) and maximum principal stress (B) [14]

Figure 3.39: Stress distribution in articular-side tear models at 60° abduction: von Mises stress (A) and maximum principal stress (B) [14]

Figure 3.40: Stress distribution in bursal-side tear models at 60° abduction: von Mises stress (A) and maximum principal stress (B) [14]

Figure 3.41: Stress distribution in intratendinous tear models at 60° abduction: von Mises stress (A) and maximum principal stress (B) [14]

In 2008, Seki et al. [108] analysed the supraspinatus tendon using a three-dimensional finite element model. The geometric shape of the humeral head was determined from computed tomography (CT). The shape of the supraspinatus tendon was determined from MRI of a shoulder at neutral rotation in adduction. The model was structured from 10840 elements and 13149 nodes. The geometric shape was composed of hexahedral volume elements, and the size of the mesh was determined based on point of interest (Figure 3.42). The material properties used were similar to previous studies [13-14]. The contact area between the tendon and the humeral head was set with a contact option, and the coefficient of friction was predetermined as 0. The distal portion of the humeral head was fixed on the x-, y-, and z-axes; and then tensile force was applied to the proximal end of the tendon in the direction of the long axis of the supraspinatus tendon. The tensile force was determined to be 10 N based on the theoretically predicted values with 7 N, 2 N and 1 N of tensile force applied to the anterior, middle and posterior part of the supraspinatus tendon respectively.

Figure 3.42: Oblique coronal section of the hexahedral meshes of the model [108]

Figure 3.43 shows the maximum principal stress in the sagittal plane of the supraspinatus tendon. The darker the color, the greater the principal stress. The stress on the articular side at the top of the humeral head was small. The maximal tensile stress of 15.0 MPa was observed on the articular side of the anterior edge of the supraspinatus tendon. The tensile stress was 1.8 MPa on the bursal side.

Figure 3.43: Maximum principal stress in the sagittal plane through the (a) anterior edge, (b) middle section, and (c) posterior section of the supraspinatus tendon. [108]

3.11 Summary

Currently, all the studies done on the footprint anatomy of the rotator cuff are on the Caucasian population. To the best of the author's knowledge, no previous work has been done on the Asian population.

From the review, all the strain studies were concentrated solely on the supraspinatus and only at limited arm positions. To the best of the author's knowledge, no previous studies measured the strains on all the rotator cuff tendons simultaneously with the glenohumeral joint intact. Additional studies are required to determine the effect of partial tears, repair and arm positions on the strain of the different rotator cuff tendons. These additional data may enable health professionals to provide better advice to the patient, for example, to avoid certain arm positions that can cause higher risk of tear propagation in the tendon before surgery and during rehabilitation.

At present, FE models of the rotator cuff tendons developed concentrated solely on the supraspinatus. A 3-dimensional FE analysis which involves the neighbouring tendons, infraspinatus and subscapularis, will present a more complete biomechanical model of the rotator cuff tendons as a whole.

4 METHODOLOGY

4.1 STRAIN MEASUREMENTS OF ROTATOR CUFF TENDONS

Nine fresh-frozen shoulders were tested on a purpose-built rig. With an overall static weight of 98.1 N loaded at the rotator cuff muscles, displacement variable reluctance transducers (DVRTs) were used to measure the strain at the anterior and posterior supraspinatus, infraspinatus, and subscapularis tendons simultaneously. Various arm positions were obtained by varying the elevation and rotation angles in the scapular, coronal and sagittal planes. Partial thickness tears were subsequently simulated through a cut at the bursal-side of the supraspinatus and were sequentially enlarged to a full-thickness tear. Single-row repair using simple stitches and horizontal stitches and double-row repair were performed on the tear subsequently. The effects of these tears and repairs on the tendon strains were obtained during abduction at the scapular plane.

This section describes the design of the purpose-built rig, the specimen preparation and the experimental methodology of this strain test.

4.1.1 Design of purpose-built rig

For the strain measurement experiment, a purpose-built rig was designed for the mounting of the shoulder joint and defining the planes, elevation and rotation angles of various arm positions. The rig design was modified from Hatakeyama's customised shoulder positioner (Figure 4.1) [79].

Figure 4.1: Schematic diagram of Hatakeyama's customised shoulder positioner [79]

The main purpose of the purpose-built rig is to hold the scapula rigidly in place and to position the humerus at various planes of specific elevation and rotational angle. Varying weights would be loaded through pulleys attached onto the rig.

Figure 4.2 shows the completed purpose-built rig. The detailed design drawings are available in Appendix A

Figure 4.2: Purpose-built Rig

The rig was designed to have the flexibility of adjusting the positions and angles of the pulleys to adapt the different lines of muscle action. To define the various humerus positions, a *humerus-positioning arc frame* is fixed onto the rig. It can be rotated through 180° about the z-axis, which covers the planes of scapula, sagittal, coronal and forward flexion. The frame allows the humerus to be elevated up to 120° . Attached to the arc frame is a rotator device, which provides the internal and external rotational angle of the humerus, up to a maximum of 90° each.

A *vertical plate* is drilled with holes for the mounting of the scapular. To accommodate the varying sizes of specimens, the position of this vertical plate can be adjusted in the anterior-posterior direction for the alignment of each humeral head to the rotation centre of the arc frame.

4.1.2 Cadaveric shoulder specimens

4.1.2.1 Source

A total of 20 fresh-frozen cadaveric shoulder specimens were obtained from the Department of Experimental Surgery Laboratory at Singapore General Hospital (SGH) for the author's project. The mean age of the specimens was 74 years (65 to 78). Four specimens were used for pilot tests and seven other specimens were not suitable for strain measurements due to inherent tendon tears or broken bones. Only nine specimens were used for strain measurements. Four were from the left shoulder and five were from the right. All the dissections and experiments related to the shoulder specimens were carried out at SGH.

4.1.2.2 Specimen Preparation and Dissection

The cadavers, which consist of the whole upper limb, were harvested and frozen at -20°C within 24 hours of death. Before dissection, each specimen was thawed at room temperature for approximately 12 hours.

All soft tissues, except the rotator cuff muscles and tendons, were removed. An initial incision (Figure 4.3) originating from the triceps' segment of the upper arm to the elbow

joint was made and the skin and underlying soft tissues were completely removed. The forearm was then disarticulated from the upper arm.

Figure 4.3: Initial incision for skin removal

For the remaining soft tissues surrounding the humeral head and scapula, care had to be taken during dissection. The skin was first removed leaving the underlying muscles, tendons and fats exposed. Next, the superficial pectoralis major, trapezius and deltoid muscles were removed. The clavicle was also detached from the acromion. The individual rotator cuff muscles and tendons, supraspinatus, infraspinatus, teres minor and subscapularis, were then identified (Figure 4.4 and 4.5).

Figure 4.4: Supraspinatus and subscapularis

Figure 4.5: Infraspinatus and teres minor

In order to have a wider range of positions tested on the glenohumeral joint, the acromium and corocoid process were clipped off (Figure 4.6) to prevent impingement of the DVRTs during experiment.

Figure 4.6: Clipped acromium and coracoid process

The specimen was moistened with saline solution every 5 to 10 minutes throughout the experimental setup and testing, which was performed in an air-conditioned room at 22°C.

4.1.2.3 Storage of specimens after use

It is important to have a proper storage of the specimen for further testing (footprint measurement, anchor pull-out strength test). Upon completion of the experiment, saline solution would be dripped onto the four muscles of the rotator cuff. A piece of dampened cotton padding would then be wrapped onto the muscles to keep them moist so as to protect the existing properties of the soft tissues. The specimen was kept in a Ziploc bag and firmly sealed to prevent air from seeping in. Finally, it was placed in the freezer at -20°C for storage.

4.1.3 Calculations of loadings for individual muscles

Past studies had used various ways to load the individual rotator cuff muscles. Bey et al. [11, 17] centered the humeral head on the glenoid by applying equal loads of 4.5 N to the subscapularis, supraspinatus and external rotator tendons. While testing the effect of arm position on the stretching of the cuff muscles, Muraki et al. [18] applied a force of 11 N to each of the infraspinatus and subscapularis tendons. Others loaded the muscles proportionally to the muscle physiological cross-sectional area [67, 109].

In this current study, the rotator cuff muscles were loaded such that the humerus would be fixed to the reference position (neutral rotation, 0° elevation) ie, zero net moment. The proportion of loads required was found with the use of an optimisation method using Microsoft Excel adapted from Mura's study [110]. Using digital vernier callipers, the widths of the humeral head in all three directions (anterior-posterior, medial-lateral, superior-inferior) were measured to determine its centre, the origin of the coordinate system for this experiment (Table 4.1).

MUSCLE SEGMENTS (J)			COORDINATES	
			FOOTPRINT INSERTION (I)	MUSCLE ORIGIN (O)
1	SUPRASPINATUS ANTERIOR	SSant	X_{I1}, Y_{I1}, Z_{I1}	X_{O1}, Y_{O1}, Z_{O1}
2	SUPRASPINATUS POSTERIOR	SSpos	X_{I2}, Y_{I2}, Z_{I2}	X_{O2}, Y_{O2}, Z_{O2}
3	INFRASPINATUS SUPERIOR	ISsup	X_{I3}, Y_{I3}, Z_{I3}	X_{O3}, Y_{O3}, Z_{O3}
4	INFRASPINATUS INFERIOR	ISinf	X_{I4}, Y_{I4}, Z_{I4}	X_{O4}, Y_{O4}, Z_{O4}
5	TERES MINOR	TM	X_{I5}, Y_{I5}, Z_{I5}	X_{O5}, Y_{O5}, Z_{O5}
6	SUBSCAPULARIS SUPERIOR	SCsup	X_{I6}, Y_{I6}, Z_{I6}	X_{O6}, Y_{O6}, Z_{O6}
7	SUBSCAPULARIS INFERIOR	SCinf	X_{I7}, Y_{I7}, Z_{I7}	X_{O7}, Y_{O7}, Z_{O7}

Table 4.1: Muscle segments and coordinates

The muscles were loaded along their line-of-actions at seven points: two lines on supraspinatus, infraspinatus and subscapularis each, one line on teres minor. Using digital vernier callipers, the coordinates of individual tendon insertions and muscle origins were measured with respect to the centre of the humeral head, the origin of the coordinate system. Figure 4.7 and 4.8 shows the direction of axes for the coordinate system and the three-dimensional diagram with forces on the glenohumeral joint respectively.

Figure 4.7: Direction of axes

Figure 4.8: Three-dimensional diagram with forces on the glenohumeral joint

A total mass of 10kg was distributed throughout the four rotator cuff muscles to derive the minimum or near zero moment about the x, y, and z axes. This is approximately 4% of the total maximum muscle forces of the rotator cuff [111]. It was observed during pilot tests that a total mass greater than 10 kg resulted in muscle tears during the experiments. These output values from the spreadsheet gave a good estimation of loads required and slight

adjustments of the loads were made to align the humerus at reference position. Table 4.2 shows the average calculated load for each muscle segment.

Optimisation method for solving rotator cuff muscles load

Objective Function:

Minimise

$$\sum_{j=7} F_j^2$$

where F_j is the individual muscle force to be solved.

With the input of the coordinates into the Excel spreadsheet, the line of action of each muscle can be derived:

$$d_{xj} = \frac{x_{oj} - x_{ij}}{D}, d_{yj} = \frac{y_{oj} - y_{ij}}{D}, d_{zj} = \frac{z_{oj} - z_{ij}}{D}$$

$$\text{where } D = \sqrt{(x_{oj} - x_{ij})^2 + (y_{oj} - y_{ij})^2 + (z_{oj} - z_{ij})^2}$$

Moments due to each muscle about the reference point:

$$M_{xj} = F_j m_{xj}, M_{yj} = F_j m_{yj}, M_{zj} = F_j m_{zj}$$

where moment arms,

$$m_{xj} = (y_{ij} d_{zj}) - (z_{ij} d_{yj}),$$

$$m_{yj} = (z_{ij} d_{xj}) - (x_{ij} d_{zj}),$$

$$m_{zj} = (x_{ij} d_{yj}) - (y_{ij} d_{xj})$$

Constraints:

$$\sum_j M_{xj}=0, \sum_j M_{yj}=0, \sum_j M_{zj}=0$$

$$\sum_j F_j = 10 \times 9.81$$

$$F_j > 0$$

Muscle segments	Mass (kg)	Load (N)
SSant	0.49	4.81
SSpos	0.59	5.79
ISsup	1.41	13.83
ISinf	1.53	15.01
TM	1.41	13.83
SCsup	1.69	16.58
SCinf	2.88	28.25

Table 4.2: Calculated load for each muscle segment

4.1.4 Suturing and mounting of specimen

After the collection of coordinates of the tendon insertions and muscle origins, the rotator cuff muscles were detached from the scapula and cut, leaving muscles of approximately 40 mm medial to the musculo-tendinous region for suturing of loading lines. Whip stitches (Figure 4.9) were used to suture along the seven lines of muscle action as described in Section 4.3.

Figure 4.9: Whip stitches

To ensure that the centre of the humeral head was aligned to the rotation centre of the rig arc frame, the length of humerus required to fit into the mounting rig was measured. The distal end of the humerus was cut to the required measurement and inserted into a polyvinyl chloride pipe by drilling holes through both bone and pipe. The bone was fixed rigidly to the pipe using bolts and nuts.

The scapula was then aligned onto the vertical mounting plate to indicate the three points of fixation. It was important to ensure that the medial border of the scapula was parallel to the z- axis (vertical) (Figure 4.10a) and the centre of the humeral head was aligned to the rotation centre of the rig arc frame (Figure 4.10b). If necessary, the vertical plate position would be adjusted.

Markings were made through the M8 holes on the plate and the three points were drilled through the scapula using a BOSCH portable hand drill. The scapula was then firmly fixed onto the plate using bolts and nuts.

The humerus was inserted into the rotator device of the rig and locked at reference position (Figure 4.10a). After mounting the shoulder specimen, the muscles were loaded according to the weights calculated in Section 4.1.3 and the positions of the pulleys were adjusted such that the loads would act along the lines of muscle action (Figure 4.10b).

Figure 4.10: Mounting of shoulder specimen with humerus at reference position

4.1.5 Differential variable reluctance transducers (DVRTs)

4.1.5.1 Specifications of DVRTs

Tendon strains were measured using linear differential variable reluctance transducers (DVRTs; M-DVRT-3, Microstrain Inc, Burlington, Vermont) [9-10, 78-79]. A total of four DVRTs were used to measure the strain of the supraspinatus (anterior and posterior), infraspinatus and subscapularis tendons simultaneously. Each DVRT outputs an analog voltage that is linearly proportional to the displacement of the magnetic core. The core and the body were attached to the tendon through two 3-mm long barbed pins (Figure 4.11). Because the core slides freely within the tube, this device had little influence on the change in length of the tendon being tested. Any change in the length of the tissue will cause the core to slide in the body, resulting in a change of output voltage. The detailed specifications of the DVRTS are placed in Appendix B.

Figure 4.11: Schematic diagram of a DVRT

The DVRTs were connected to a four-channel chart recorder (MB-SMT-4-EURO, MicroStrain, Inc.) to record the voltage output data during the test. They were calibrated prior to the experiment as shown in Appendix C and the distance between the barbs are given in the Table 4.3.

Supraspinatus (articular)	SSar-ant	Channel 1	Barb distance = $-0.3669x + 6.4368$	x = voltage value (V)
Supraspinatus (anterior)	SSbur-ant	Channel 2	Barb distance = $-0.3499x + 7.3713$	
Supraspinatus (posterior)	SSbur-pos	Channel 3	Barb distance = $-0.3638x + 7.7982$	
Infraspinatus	IS	Channel 4	Barb distance = $-0.3457x + 6.9627$	
Subscapularis	SC	Channel 5	Barb distance = $-0.3823x + 6.5005$	

Table 4.3: Distance between barbs (in mm)

Strain is defined according to the equation below:

$$\text{Strain} = \frac{\text{New barb distance} - \text{Initial barb distance}}{\text{Initial barb distance}}$$

The initial distance is the length between the two barbed points of the transducer with the humerus at the reference position and is used as the reference ‘zero’ position used in the calculation of tendon strain. During the experiments, the distances between the two barbed points vary between 5 to 9 mm.

4.1.5.2 Insertion of DVRTs

To measure the anterior articular side of the supraspinatus, the bicep tendon was removed first, leaving a small gap between the bicipital groove and the rotator interval. A trough was created at the humeral head (Figure 4.12a) and the gap at the bicipital groove was enlarged using a drill to provide a tunnel for the insertion of the DVRT at the articular side of the supraspinatus (Figure 4.12b and c).

Before insertion of the DVRTs, the specimen was pretensioned with the respective loads which pulled the tendon medially. The DVRTs were orientated parallel to the line of muscle action and were inserted with the humerus at reference position. After insertion, the DVRTs were sutured with surgical suture into the tendons to avoid loosening and eventually falling off from the tendons. Pilot tests had shown no significant effect of suturing on the strain readings of the tendon.

Figure 4.12: Procedure to insert DVRT at anterior of the articular side of supraspinatus

For the bursal portion of the supraspinatus, two DVRTs (Channel 2 and 3) were placed at the anterior and posterior centre of the tendon (Figure 4.13a), spanning the critical zone

[3]. For the infraspinatus and subscapularis, one DVRT (Channel 4 and 5 respectively) was placed at the centre of each tendon width. For the positions of the DVRTs, instead of using absolute distances measured from the tendon insertions [78], distances proportioned to the tendon length, as shown in Figure 4.13b, were used. This is a better method to standardise the DVRT positions as it can accommodate to the varying tendon sizes found in separate shoulder specimens.

Figure 4.13: Positions of DVRTs (plan view)

4.1.6 Experimental Variables

4.1.6.1 Arm positions

Figure 4.14: Plan view of planes used in experiment

The humerus was elevated in the scapular, coronal, and sagittal planes (Figure 4.14). The scapula plane was defined to be inclined 45° to both the coronal and sagittal planes. Arm elevation angles were 0° , 15° , 30° , 45° and 60° relative to the scapula, simulating approximately 0° , 15° , 30° , 60° and 90° of arm elevation relative to the trunk, respectively [112]. The order of the elevation plane was 1) scapular plane, 2) coronal plane, and 3) sagittal plane. After tests in one plane were completed, the humerus was brought back to the reference position before the measurements in the next plane were started. At 0° elevated position, the arm was manually rotated from 30° of external rotation to neutral, and then to 30° and 60° of internal rotation. The test configurations are shown in Table 4.4.

Plane	Elevation angles	Rotation angles	Tendon conditions
Coronal	0°, 15°, 30°, 45°, 60°	neutral	intact
Sagittal	15°, 30°, 45°, 60°	neutral	intact
Scapular	15°, 30°, 45°, 60°	neutral	intact
	0°	ext 30°, int 30° & 60°	intact
	0°, 15°, 30°, 45°, 60°	neutral	ant 2mm tear
	0°, 15°, 30°, 45°, 60°	neutral	ant full tear
	0°, 15°, 30°, 45°, 60°	neutral	single- row repair
	0°, 15°, 30°, 45°, 60°	neutral	double- row repair

Table 4.4: Test configurations

4.1.6.2 Rotator cuff tears

A full set of data with all the 16 arm positions was first gathered with the rotator cuff tendons intact. Following that, three types of simulated tears were made on the bursal portion of the supraspinatus tendon at the critical zone described by Codman [3]. For each tear, strain readings were collected with the humerus elevated in the scapular plane. A 2-mm deep partial thickness tear was first cut on the anterior supraspinatus, 1/2 width of the tendon in the anterior-posterior direction (Ant 2mm tear) (Figure 4.15). This tear mimicked a partial-thickness tear on the bursal side of the supraspinatus due to subacromial impingement. Subsequently, this 2-mm cut was extended to a full-thickness tear at the anterior portion of the SS (Ant full tear). Cuts were made using surgical knives and dimensions of cuts were measured using digital vernier calliper.

Figure 4.15: Position and width of simulated tear

4.1.6.3 Rotator cuff repairs

Two repair techniques were performed on the complete tear: single-row repair using Anchor I (5.0mm SPIRALOK™ w/ORTHOCORD™, DePuy Mitek, Inc) and a double-row repair with the addition of Anchor II (VERSALOK™ Anchor w/ ORTHOCORD™, DePuy Mitek, Inc) (Figure 4.16 and 4.17).

Figure 4.16: Anchors positions on the humeral head

Figure 4.17: (a) Single-row repair (b) Double-row repair

4.1.7 Data collection

Pilot results had not shown significant hysteresis during testing cycles, but the results were always recorded with increasing elevation angle, and rotated from external to internal rotation. After setting up for each test configuration, the system was preconditioned by elevating the shoulder up and down for 25 times to minimise the viscoelastic effect of the soft tissue [109]. The output of the DVRTs was recorded over three cycles of elevation for each plane and simulated tear type and the average output was taken.

4.2 ANTHROPOMETRY AND FOOTPRINT MEASUREMENT

4.2.1 Width and thickness

Tendons thickness and width were measured using a digital vernier calliper at three regions (Figure 4.18), namely

- Footprint- Thickness and width of the tendon proximal to the region of insertion of tendon with the humerus.
- Centre- Thickness and width of the tendon in the region between insertion of tendon with the humerus and the muscle.
- Muscle- Thickness and width of the tendon proximal to its respective muscle.

Figure 4.18: Various regions of the rotator cuff

4.2.2 Length

The tendons' length were measured using a digital vernier calliper. The length was measured in various regions, namely (Figure 4.19)

- Anterior
- Posterior
- Superior
- Inferior
- Centre

Figure 4.19: Anatomical Position of Rotator cuff

4.2.3 Footprint

The shoulders used in the strain measurement experiments were further dissected to obtain the footprint measurements. Four specimens were used to evaluate the various methods of footprint measurement in the preliminary study. The best method was chosen for the remaining 11 specimens.

Out of the various methods reviewed, the particle layer, grid and planar area method were selected for preliminary tests. For the particle layer method, dental wax (Figure 4.20i) was selected due to its adhesive properties and ease of availability. Clay (Figure 4.20ii) was also used to effectively evaluate and quantify the results obtained.

Figure 4.20: i) Solid and melted dental wax; ii) Clay moulding

As for the planar method, butter paper and tracing paper were utilized due to their translucent properties, easy adherence to the contours of the rotator cuff, smooth and attractively hard surfaces to work on and relatively low cost.

Tracing and butter paper were employed to obtain the 2-dimensional planar area of the rotator cuff. Finally, they were coated with clay and dental wax to obtain the 3-dimensional planar area. They were then studied, with particular attention paid to the relationship of the insertion to the articular surface and the tuberosity.

Calculation of the planar area and dimensions

The image analysis software, Digimizer® 3.7.1.0 (MedCalc Software, Belgium), was utilized to facilitate the calculation of the planar areas of the stencils obtained from the respective methods employed. In comparison to the traditional method which requires tracing out the area on a grid paper and manually counting it, Digimizer is an easy-to-use and flexible image analysis software package that allows precise manual measurements as well as automatic object detection with measurements of object characteristics.

Digimizer enabled the author to define the unit of measurement and plot proximate fit lines around the scanned image to measure its area. Pilot studies on paper cutouts measuring 3 cm by 3 cm and 1 cm by 1 cm were done to verify the accuracy and its ability to reproduce similar results repetitively. Thereafter, the respective stencils obtained from the stated methods were scanned and uploaded into the software to calculate the planar area (Figure 4.21).

Figure 4.21: Print screen of the software “Digimizer”

The maximum length and width of footprints (Figure 4.22) as tabulated in Table 4.5 were also calculated [74].

Dimensions	SS	IS	TS	SC
Maximum length	Maximum anterior to posterior distance	Maximum distance between the lateral most vertex of superior margin to the medial most vertex of inferior margin	Maximum superior to inferior distance	Maximum superior to inferior distance
Maximum width	Maximum medial to lateral distance	Maximum distance between the medial most vertex of superior margin to the lateral most vertex of inferior margin	Maximum medial to lateral distance	Maximum medial to lateral distance

Table 4.5: Maximum length and width of the footprint as per its anatomic orientation

Figure 4.22: Traces and dimensions of the delineated footprint for a shoulder specimen

4.3 TENSILE TEST OF ROTATOR CUFF

4.3.1 Materials and equipment

The tensile test of the rotator cuff tendons was done in the biomechanics laboratory in Republic Polytechnic using the Instron 5848 Microtester.

The raw materials used in the experiment include:

- 1) 8 human cadaveric shoulder rotator cuff tendons
- 2) Saline solution
- 3) Ethanol solution
- 4) Sterile surgical gloves
- 5) Sterile surgical masks
- 6) Cotton sheets
- 7) Ziploc storage bags
- 8) Cotton padding
- 9) Permanent markers

The equipments used in the experiment include:

- 1) Instron Machine 5848
- 2) BlueHill software for data collection
- 3) Surgical tools for dissection
- 4) Cadaveric dissection board
- 5) Storage freezer

- 6) Purpose-built serrated jaw nylon clamp [113] (Figure 4.23)
- 7) Purpose-built humeral grip clamp

Figure 4.23: Purpose-built serrated jaw clamp

4.3.2 Procedures

Eight fresh frozen cadaver shoulders with no radiological evidence of glenohumeral osteoarthritis were obtained for the study. Specimens with rotator cuff tears on inspection were excluded from the study to eliminate the influence of longstanding soft tissue degeneration. During dissection, preparation and testing, the specimen was moistened using physiologic saline solution. All soft tissues were removed except the rotator cuff tendons.

The tendon was carefully separated from the joint capsule bluntly and by means of sharp dissection close to its insertion simultaneously by pulling on the tendon as well as the capsule to minimize injury to the tendon surface. The identified tendons on which the biomechanical testing was carried out on are the supraspinatus, infraspinatus, subscapularis and teres minor (Figure 4.24).

Figure 4.24: Rotator cuff tendons

Figure 4.25: Tendons sutured with wire mesh

After careful identification of the respective tendon, the tendons were further dissected to supraspinatus (anterior and posterior), infraspinatus (superior and inferior), subscapularis (superior and inferior) and teres minor. Brass wire mesh was sutured onto each musculotendinous junction of the rotator cuff tendons (Figure 4.25). The specimen was then mounted onto the purpose-built grip and the tendon was clamped at the wire mesh sutured surface by the serrated nylon jaw clamp at 0° glenohumeral angle (Figure 4.26).

Figure 4.26: Tensile test setup

Each specimen was at least 20 mm in length. Testing was done immediately after balancing the load and extension on the BlueHill software and 10 cycles of preconditioning within 10% strain. All the tensile strength tests were conducted at a rate of 1 mm/min. To maintain a consistent environment throughout the testing, the experiment was performed in a chamber. The temperature during testing was approximately 20°C and relative humidity was 50-60%. Between the tests, the tissue was moistened with saline to avoid tissue desiccation.

The displacements of the crossheads of the material testing machine were recorded. Load-displacement and stress-strain data were analyzed using the Bluehill software. The elastic modulus was calculated from the slopes of the most linear portions of the load-displacement and stress-strain curves, respectively.

The load-displacement data were used to obtain the stress-strain plots. The cross-sectional areas of the tendons were assumed to be an ellipse. The mean moduli of different tendon

regions were analyzed and compared using analysis of variance (ANOVA) to determine whether there are any significant differences between the tendon regions (anterior/posterior, superior/inferior), and between the four different tendons (supraspinatus, infraspinatus, teres minor, subscapularis).

4.4 FINITE ELEMENT ANALYSIS OF ROTATOR CUFF

In this section, the procedures of preparing the 3D models of the humerus, subscapularis, supraspinatus, infraspinatus and teres minor tendons are illustrated. These include the processing of MRI images into solid models, which would be used for Finite Element Analysis (FEA) simulation.

The FEA simulation was documented at every step. The created model was compared and verified with the experimental results. Figure 4.27 summarizes the FE work procedures.

Figure 4.27: Flowchart for the FEA of the rotator cuff

4.4.1 Creating 3D representation from MRI

A set of MRI scans of a right shoulder was obtained from a healthy Chinese male subject for this study (Figure 4.28). It had a resolution of 320 x 320 pixels at 0.478 mm interval.

Figure 4.28: MRI of an anterior view of a right shoulder

A well-established 3D image rendering, processing and analysis software, MIMICS (Materialise's Interactive Medical Image Control System) version 10 (Materialise, Leuven, Belgium), was utilized in this process. MIMICS can process both CT and MRT scans as well as other several types of imagery formats. It is capable of extracting object boundaries with the aid of 3D image segmentation functionality. It virtually creates both 3D surface and 3D volume of each object segmented so that it can be used for visualisation, measurement or qualitative analysis. Figure 4.29 presents the main steps used in MIMICS. Thresholding means that the segmentation object (visualised by a colored mask) will contain only those pixels of the image with a value higher than or equal to the threshold value. As bone produced a denser image than soft tissue in MRI, the segmented mask of the humeral head could be obtained by setting a higher threshold values (Figure 4.30).

Figure 4.29: Flowchart of the general steps in MIMICS

Figure 4.30: Segmented mask of the humeral head created through thresholding

Mask segmentation for the tendons and glenoid was created manually on each MRI slide (Figure 4.31). The 3D representation was calculated and smoothened. The process was repeated until an ideal model was created. The supraspinatus, infraspinatus and teres minor (SIT) were modeled as a single part similar to the actual tendons.

Figure 4.31: Mask segmentation

4.4.2 Exporting into Solidworks software

The point cloud file of the 3D model was exported into SolidWorks® 2009 (Dassault Systemes SolidWorks Corp., Velizy, France) (Figure 4.32).

Figure 4.32: Point cloud parts of humeral head and tendons

Using the SolidWorks software's ScanTo3D functionality, the point cloud files were converted to solid part models of the rotator cuff tendons. Figure 4.33 gives the overview of the ScanTo3D process.

Figure 4.33: Overview of the ScanTo3D Process

The individual parts of the humeral head, glenoid and rotator cuff tendons created (Figure 4.34) were exported as a CAD (computer-aided design) model, format with an extension of IGES, to a commercially available finite element software for preprocessing and meshing generation.

Figure 4.34: Volume rendering of the solid model

4.4.3 Preprocessing

Software Abaqus/CAE 6.8-1 (ABAQUS Inc., Providence, Rhode Island, USA) is used as the main finite element solver platform for this project. Abaqus/CAE is a commercial software package for finite element analysis that can quickly and easily create, edit, monitor, diagnose, and visualize advanced finite element analyses. The user friendly interface integrates modeling, analysis, job management, and results visualisation in a consistent, easy-to-use environment that is simple to learn for new users. Users can create geometry, import CAD models for meshing, or integrate geometry-based meshes that do not have associated CAD geometry. Interfaces for SolidWorks enable seamless synchronization of CAD and CAE assemblies into Abaqus.

Part instances of the individual parts were created and assembled. The Boolean operations were used to ensure that there were no intersecting boundaries between the assembled parts. The origin of the three-dimensional coordinate system was defined at the centre of the humeral head with the X axis pointing to lateral, Y axis to anterior and Z axis to inferior. The tendons were sectioned for the ease of implementing load (Figure 4.35).

Figure 4.35: Assembly of the sectioned rotator cuff tendons

4.4.4 Meshing

After the solid model was developed, generation of the mesh was carried out. The FE mesh was obtained by discretising the solid model using a top-down free meshing technique. Top-down meshing generates a mesh by working down from the geometry of a part or region to the individual mesh nodes and elements. As the tendons have irregular and complex shapes, the flexible free meshing technique was used. It uses no pre-established mesh patterns and can be applied to almost any model shape.

As the analysis was concentrated on the tendons, the humeral head was modeled using quadratic quadrilateral shell elements to reduce the number of elements and consequently save analysis and post-processing times. The geometric shape of the glenoid and tendons

were composed of linear tetrahedral volume elements, and the size of the mesh was determined based on point of interest (Figure 4.36). As the focus of the model was on the rotator cuff tendons, the mesh sizes of the tendons were smaller compared to the humerus. Within the tendons, mesh sizes were relative smaller at critical areas such as the footprints where the contours were not as smooth.

Figure 4.36: FE model of rotator cuff tendons

Convergence tests were performed and Table 4.6 summarises the types and number of elements and nodes used to model the various components of the humeral head, glenoid and rotator cuff tendons.

Component Name	Element Type	Number of Elements	Number of nodes
Humeral head	Quadratic quadrilateral	3103	9083
Glenoid	Linear tetrahedral	7534	1834
SIT		105520	20875
Subscapularis		41122	8417

Table 4.6: Types and number of elements and nodes used in FE model

4.4.5 Defining material properties

Material properties of the various components are the next important consideration following the generation of the FE model. The humeral head was modeled to be the shell of the cortical bone. Table 4.7 summarises the material properties assigned to each part. The Young's modulus of the rotator cuff tendons were taken from the experimental results of the tensile test. As there was no significant difference among the tendons, the average modulus was used.

Component name	Young's Modulus E (MPa)	Poisson's Ratio ν
Cortical bone [13]	13800	0.3
Glenoid [114]	100	0.263
Rotator cuff tendons	72.8	0.497

Table 4.7: Material properties assigned to each part

All the components were assumed to be homogenous, isotropic and linear elastic materials.

4.4.6 Boundary and loading conditions

Following the FE model generation and material property assignment, the boundary and loading conditions were applied to simulate the loadings applied in the strain experiments. By comparing the results of both the FE and experimental results, the FE model could be validated. The surfaces between the humeral head and the tendons at the footprints were constrained with tie contact. The interaction between the tendons and humeral head and between the glenoid and humeral head were set to surface-to-surface contact with finite sliding and normal behavior. Nodes at the centre of each tendon region near the loading end were constrained in the z-direction (Figure 4.37). This simulates the loading direction constrained by the scapula and the pulleys during the experiment.

Figure 4.37: Nodes constrained in the z-direction at the centre of each tendon region

Both the humeral head and glenoid were set as rigid bodies. The glenoid was fixed on all three axes and not allowed to rotate. Tensile force was applied to each tendon according to the average load applied during the experiments (Table 4.8 and Figure 4.38)

Tendon	Load (N)
Supraspinatus	10.6
Infraspinatus	28.8
Teres Minor	13.8
Subscapularis	44.8

Table 4.8: Load applied to each rotator cuff tendon

Figure 4.38: Loading conditions of the rotator cuff tendons

There were two steps in the analysis. During the first step, the humeral head was fixed in all three axes and restricted from rotation. This simulates the neutral condition of the experimental set-up. The humeral head was rotated to various angles (15° , 30° , 45° , 60°) about the Y-axis during the second step to simulate the elevation of the humerus in the scapular plane.

4.4.7 FE strain analysis

Two nodes at each surface of the tendon region were chosen to simulate the two points inserted by each DVRT during experiment (Figure 4.39). The distances between the two points were calculated at elevation angles of 0° , 15° , 30° , 45° and 60° and the strain at each elevation angle was calculated with respect to the neutral position, 0° . The process was repeated with another two set of nodes and the mean strain was taken. The obtained FE analysis results were then compared with the experimental results to validate current FE model of the rotator cuff tendons.

Figure 4.39: Nodes chosen to calculate strain at each tendon region

Strain profile across the anterior supraspinatus, from the articular to the bursal side at elevation angle of 60° , was also calculated.

5 RESULTS

5.1 STRAIN MEASUREMENTS OF ROTATOR CUFF TENDONS

5.1.1 Arm positions

Scapular plane: With increasing elevation angle from 0° to 60° , the strain on the SSar-ant increased to +11.2% whereas the strains of the SSbur-ant and SSbur-pos decreased to -2.3% and -4.8%, respectively (Figure 5.1). There is no significant difference between the anterior and posterior strains of the bursal side ($p > 0.05$). There is also no significant change in the strains of the infraspinatus and subscapularis during abduction in the scapular plane ($p > 0.05$) (Figure 5.2).

Figure 5.1: Effect of elevation angle on the supraspinatus strain at various positions in the scapular plane

Figure 5.2: Effect of elevation angle on the strain of posterior rotator cuff tendons in the scapular plane

Sagittal plane: With increasing elevation angle from 0° to 60° , the strains of the SSar-ant, SSbur-ant and SSbur-pos decreased to -2.1%, -4.3% and -4.7%, respectively. There is no significance difference between the supraspinatus strains ($p > 0.05$). There is no significance change in the strains of infraspinatus and subscapularis ($p > 0.05$) (Figure 5.3).

Coronal plane: With increasing elevation angle from 0° to 60° , the strain on the SSar-ant increased to +5.4% whereas the strains of SSbur-ant and SSbur-pos at the bursal side decreased to a maximum of -5.8% and -11.0%, respectively. There is significant difference between the strains of the SSbur-ant and SSbur-pos from 30° to 60° elevation ($p < 0.05$). The strain of SC decreased to -7.7% with increasing elevation angle from 0° to 60° . There is no significance change in the strains of infraspinatus ($p > 0.05$) (Figure 5.4).

Figure 5.3: Effect of elevation angle on the strain of rotator cuff tendons in the sagittal plane

Figure 5.4: Effect of elevation angle on the strain of rotator cuff tendons in the coronal plane

Rotation: As the humerus was rotated from an external rotation of 30° to an internal rotation of 60° , the tendons at the anterior side, SSar-ant, SSbur-ant and SC, decreased from +1.0%, +0.2% and +0.9% to -5.7%, -4.6% and -9.3%, respectively while the tendons at the posterior side, SSbur-pos and IS, increased from -3.6% and -1.4% to +0.5% and +4.6%, respectively (Figure 5.5).

Figure 5.5: Effect of rotation angle on the strain of the rotator cuff tendons in neutral position

5.1.2 Simulated tears

In general, the strain increased with a propagating tear at the anterior SS (Figure 5.6-5.8). With respect to the intact strains, an anterior 2 mm partial tear at the anterior side resulted in a 3.1% strain increment at the SSar-ant (Figure 5.6), and no significant change at the SSbur-ant (Figure 5.7) and SSbur-pos (Figure 5.8).

Following an anterior full tear, the strain increased further by 1.1% for the SSbur-pos (Figure 5.8).

Figure 5.6: Effect of anterior 2mm partial tear on SSar-ant strain

Figure 5.7: Effect of anterior 2mm partial tear on SSbur-ant strain

Figure 5.8: Effect of anterior 2mm partial tear and full tear on SSbur-pos strain

5.1.3 Repairs

Comparing between the intact strains and a single row repair at 0° , the SSar-ant strain increased by 3.0% while that of the SSbur-ant decreased by -4.17%. With a double-row repair, the strain was almost restored to its intact condition for the SSar-ant at -1.0%, while it increased to -1.8% for the SSbur-ant, nearing the intact strain value (Figure 5.9 and 5.10).

Figure 5.9: Effect of repair on SSar-ant strain

Figure 5.10: Effect of repair on SSbur-ant strain

5.2 ANTHROPOMETRY AND FOOTPRINT MEASUREMENT

5.2.1 Width and thickness

The width and thickness of the tendons are summarised in Table 5.1. Mean width and thickness of the divided regions (footprint, central and muscle) were used for comparison. Statistical tests revealed that the SC has the largest width ($p < 0.05$). No significant difference ($p > 0.05$) was noted between the width of the SS and IS. TM has the lowest width ($p < 0.05$). ANOVA test on the thicknesses indicated no significant difference ($p > 0.05$) between thicknesses of the tendons.

Tendon	Mean Width (mm)	Mean Thickness (mm)
SS Footprint	23.35 ± 4.24	5.25 ± 1.23
SS Central	27.27 ± 4.33	4.24 ± 1.31
SS Muscle	27.42 ± 4.34	5.11 ± 1.14
IS Footprint	25.45 ± 4.44	4.43 ± 1.35
IS Central	25.24 ± 5.21	4.34 ± 1.33
IS Muscle	28.01 ± 5.14	5.23 ± 1.41
TM Footprint	20.24 ± 5.21	3.14 ± 1.36
TM Central	22.31 ± 5.17	4.28 ± 1.39
TM Muscle	22.23 ± 5.24	4.23 ± 1.23
SC Footprint	34.43 ± 7.23	5.14 ± 1.16
SC Central	38.27 ± 6.25	5.38 ± 1.41
SC Muscle	39.41 ± 7.23	5.25 ± 1.26

Table 5.1: Width and thickness of the tendons (n = 19)

5.2.2 Length

Table 5.2 presents the length of the tendon regions. Mean length of the divided regions was used for comparison. Statistical tests revealed that the IS has the longest length ($p < 0.05$). No significant difference ($p > 0.05$) was noted between the length of the TM and SC. SS has the shortest length ($p < 0.05$).

Tendon region	Mean length (mm)
SS Anterior	32.21 ± 7.32
SS Central	29.34 ± 6.43
SS Posterior	31.42 ± 6.35
IS Superior	40.25 ± 6.36
IS Central	40.35 ± 6.23
IS Inferior	40.43 ± 6.42
TM Superior	35.51 ± 6.27
TM Central	33.51 ± 6.32
TM Inferior	32.11 ± 6.41
SC Superior	37.33 ± 6.35
SC Central	33.35 ± 6.23
SC Inferior	32.26 ± 5.45

Table 5.2: Length of the tendons (n = 19)

5.2.3 Footprint

The various methods implemented in the study of obtaining the planar area of the respective footprint of the tendons yield fairly similar results (Figure 5.11). In each case the difference is about 1% of the mean area, suggesting little practical difference among the methods. For the remaining specimens, the tracing paper method was applied as it was the most convenient method.

Figure 5.11: Mean area obtained from the various methods for the respective tendon (n=4)

Footprint's dimensions and surface area are presented in Table 5.3. Subscapularis tendon has the largest footprint area ($p < 0.05$). Teres minor has the smallest footprint area ($p < 0.05$). No significant difference was found between infraspinatus and supraspinatus footprint areas ($p > 0.05$).

Tendon	Dimension (as defined in Table 4.5)		Surface area (mm ²)
	Maximum length (mm)	Maximum width (mm)	
Supraspinatus (SS)	21.42 ± 3.19	15.29 ± 2.22	317 ± 127
Infraspinatus (IS)	22.14 ± 3.24	16.32 ± 2.31	361 ± 74
Teres minor (TM)	20.37 ± 3.16	17.36 ± 2.44	221 ± 50
Subscapularis (SC)	42.25 ± 5.36	22.31 ± 3.43	664 ± 66

Table 5.3: Dimensions and surface area of the footprint (n = 19)

5.3 TENSILE TEST OF ROTATOR CUFF TENDONS

Statistical analysis on elastic moduli of the divided regions of the same tendon revealed no significant difference ($P > 0.05$). The elastic modulus of each tendon was estimated by calculating the mean modulus (Table 5.4) of divided regions (SS anterior and posterior, IS superior and inferior, SC superior and inferior). ANOVA test on the mean elastic moduli revealed no significant difference ($P > 0.05$) between the subscapularis, supraspinatus and infraspinatus tendons. Teres minor had the least modulus value ($P < 0.05$).

Tendon	Region	Mean (MPa)		
Supraspinatus (SS) (n = 5)	Anterior	73.88 ± 21.72	69.56	72.78
	Posterior	65.24 ± 14.71		
Infraspinatus (IS) (n = 8)	Superior	75.79 ± 20.84	80.54	
	Inferior	85.29 ± 18.92		
Subscapularis (SC) (n = 8)	Superior	65.99 ± 31.44	68.24	
	Inferior	70.49 ± 43.63		
Teres minor (TM) (n = 8)	NA	19.56 ± 14.33		

Table 5.4: Elastic moduli of the rotator cuff tendons

5.4 FINITE ELEMENT ANALYSIS

Figure 5.12 shows how the maximum principal stress of the rotator cuff tendons varies from 0° to 60° . In general, the tensile stresses within the tendons increased with the increase in glenohumeral angle.

Figure 5.12: Maximum principal stress of the rotator cuff tendons from 0° to 60°

Figure 5.13 shows the maximum principal stress of the rotator cuff tendons at 0° . The maximum tensile stress of the supraspinatus tendon was 3.2 MPa (Figure 5.14), which was observed on the articular side of the anterior edge near the footprint. The tensile stress was 0.2 MPa on the bursal side.

Figure 5.13: Maximum principal stress of the rotator cuff tendons at 0°

Figure 5.14: Maximum principal tensile stress of the supraspinatus at 0°

Figure 5.15 and 5.16 show the orientation and maximum principal stress of the rotator cuff tendons at elevation angle of 60° respectively.

Figure 5.15: Rotator cuff tendons at elevation angle of 60°

Figure 5.16: Maximum principal stress of the rotator cuff tendons at 60°

At 60°, the maximum tensile stress of the supraspinatus was 6.0 MPa, located at the articular side of the posterior edge near the footprint insertion. In addition, the maximum tensile stress for the subscapularis and infraspinatus was located at the articular side of the inferior edge near the insertion.

Figure 5.17 to 5.21 compares the strain results between the experiment and FE for the various rotator cuff tendons. Both experiment and FE results show similar trend with a correlation of 0.85.

Figure 5.17: Comparison of results between experiment and FE for SSar-ant

Figure 5.18: Comparison of results between experiment and FE for SSbur-ant

Figure 5.19: Comparison of results between experiment and FE for SSbur-pos

Figure 5.20: Comparison of results between experiment and FE for IS

Figure 5.21: Comparison of results between experiment and FE for SC

At 60°, the strain varied linearly across the anterior supraspinatus from the articular to bursal surface (Figure 5.22). Interpolating from the graph, 0% strain was located at two-third of supraspinatus thickness from the articular surface.

Figure 5.22: FE strain profile across anterior supraspinatus at elevation angle of 60°

6 DISCUSSION

6.1 STRAIN MEASUREMENTS OF ROTATOR CUFF TENDONS

Various strain studies on the rotator cuff have been performed previously [9-11, 17, 19, 78, 109]. None had measured the strains on the individual rotator cuff tendons simultaneously and shown the effect of supraspinatus tears and repairs on other cuff tendons with the glenohumeral joint intact. To measure the strain of both the bursal and articular sides, the supraspinatus were isolated in past studies. The isolation of supraspinatus removed the interactions with other structures such as the rotator interval and the overlapping with the infraspinatus. Histological data suggested that in vivo, supraspinatus loads are also transmitted through the infraspinatus and capsule [42]. Thus, it is important to keep the rotator cuff tendons intact for more accurate strain readings. The methods utilised in the current project allowed the simultaneous measurement of the articular and bursal surfaces of the supraspinatus with the glenohumeral joint intact.

6.1.1 Arm positions

The results showed the variation of strains with respect to different arm positions. In general, strain of SS at the bursal side reduced with increasing elevation angle while it increased at the articular sides in scapular (Figure 5.1) and coronal (Figure 5.4) planes and decreased in sagittal plane (Figure 5.3). This trend coincides with Reilly's finding in the scapular plane [9]. In addition, there was significant difference between the strain at the anterior and bursal supraspinatus at the higher elevation angles of the coronal plane (Figure 5.4). It could be due mainly to the anatomical aspect of the glenohumeral

joint (Figure 6.1). Moreover, the anatomical configuration of the SS muscle–tendon complex was revealed to be inhomogeneous, with the modulus of elasticity of the bursal layer significantly lower than that of the articular layer [59] and a thicker anterior portion adjoining the thinner and wider posterior side [115]. In 1939, Lindblom and Palmer [116] first suggested that differential loading of the articular and bursal layers of the supraspinatus tendon may result in a shearing effect between them. This may contribute to the propagation of intratendinous defects that are initiated by high articular side strains and ultimately delamination of the tendon.

Figure 6.1: Tensile and compressive strains within the supraspinatus

Similarly, during internal rotation, due to the anatomical aspect of the tendons, strains at the bursal surfaces of the subscapularis and anterior supraspinatus decreased as they were curved in and compressed. The infraspinatus and posterior supraspinatus increased due to tension (Figure 6.2).

Figure 6.2: Tensile and compressive strains within the tendons during internal rotation from plan view of the humeral head

6.1.2 Simulated tears

With a 2 mm partial bursal tear at the anterior SS, the strain of the SSar-ant increased (Figure 5.6) but there is no significant change in the SSbur-ant and SSbur-pos (Figure 5.7 and 5.8). The full-thickness tear at the anterior SS was designed to replicate the results of an impingement lesion. In vivo, the tear morphology is more complex, with less well-defined margins. A strain increase was recorded posterior to the full-thickness tear (Figure 5.8) due to the redistribution of the load to the remaining intact SS (Figure 6.3). This coincides with Reilly et al.'s [10] results. The change in tendon strain patterns implied that a loss of tendon cross-sectional area increases strain and therefore, stresses in the remaining tendon. This results in greater stress concentrations and susceptibility to tensile failure.

Figure 6.3: Strain redistributed due to tear at anterior SS

6.1.3 Repairs

Sutures at the single-row repairs pulled the supraspinatus towards the first anchor within the bone (Figure 6.4), causing strains to increase at the articular side (Figure 5.9) and decrease at the bursal side (Figure 5.10).

Figure 6.4: Sutures at the single-row repairs

Figure 6.5: Sutures at the double-row repairs

The double-row repair covered a greater contact area with the sutures being pulled over the tendon by the second anchor (Figure 6.5). As a result, the gap of the tear was further reduced and caused the bursal side strain to increase (Figure 5.10) while at the same time reducing the articular side strain (Figure 5.9), restoring to its intact condition.

Double-row rotator cuff repair techniques integrate a medial and lateral row of suture anchors in the repair configuration. From the current strain results, single-row repair increases the strain difference between the articular and bursal surfaces of the supraspinatus tendon. Double-row repair technique produces better results in restoring tendon strains. The current literature also reveals that the biomechanical properties of a double-row rotator cuff repair are superior to a single-row repair [117]. These include increased load to failure, improved contact areas and pressures, and decreased gap formation at the footprint healing. Clinical studies, however, have yet to demonstrate a substantial improvement over single-row repair with regard to either the degree of

structural healing or functional outcomes [118]. Depending on the size of the tear, there appears to be a benefit of structural healing when an arthroscopic rotator cuff repair is performed with double-row fixation as opposed to single-row fixation. The patient's age, functional demands, and other quality-of-life issues should be considered before deciding which surgical method to employ. Due to the higher strain difference within the suprapinatus, elevation of arms at higher angles should be avoided after surgical repair of the tendon.

6.1.4 Limitations

The extent of pre-existing degenerative change in the tendons was not quantified although they were macroscopically normal. Since the specimens were from an elderly population, the extrapolation of results to a younger active population may not be justified. The number of specimens tested was limited and further reduced due to inherent tears found in some of the specimens. The DVRTs could only measure the linear elongation between the barbs and not the deformation of the tendon when it wraps around the humeral head. The trough created in the humeral head may also affect the actual strain readings due to the absence of transverse force from the humeral head.

6.2 ANTHROPOMETRY AND FOOTPRINT MEASUREMENT

6.2.1 Dimension of tendons

The values obtained in the current study for IS and TM tendon's thickness was higher ($p < 0.05$) than those reported by Halder et al. [93]. The SS tendon's width and thickness obtained was higher ($p < 0.05$) than those reported by Itoi et al [107] (Table 6.1).

Studies	Thickness (mm)			Width (mm)
	IS	TM	SS	SS
Current study	4.7	3.9	4.9	26.0
Halder et al. [93]	2.9	3.6	-	-
Itoi et al. [107]	-	-	3.3	21.9

Table 6.1: Comparison of thickness and width of tendons between current and past studies

Current IS and SS tendon lengths were consistent ($p > 0.05$) with those reported by Langenderfer et al. [119]. However, TM length was higher ($p < 0.05$) (Table 6.2).

Studies	Length (mm)		
	IS	TM	SS
Current study	40.3	33.7	31.0
Langenderfer et al. [119]	22.7	36.9	34.4

Table 6.2: Comparison of length of tendons between current and past studies

6.2.2 Footprint

Arthroscopic repair of the rotator cuff tendons has become more prevalent in recent years. The knowledge of the average footprint area of each tendon helps the surgeon to restore torn tendons to their functional anatomic positions.

Current values of footprint dimensions were consistent with values reported by Curtis et al. [76] and D'Addesi et al. [120] (Table 6.3). Footprint surface areas were higher than those reported by Dugas et al. [74] (Table 6.4). This could be due to the different methods used in the measurement. The reduction of the 3-dimensional data into 2-dimensional space would cause an overall underestimation of area in the measurement of Dugas et al's study. There was no significant difference between Asian and Caucasian rotator cuff tendon footprint dimensions.

Studies	Maximum length (mm)				Maximum width (mm)			
	SS	IS	TM	SC	SS	IS	TM	SC
Current study	21.4	22.1	20.4	42.3	15.3	16.3	17.4	22.3
Curtis et al. [76]	23	29	29	40	16	19	21	20
D'Addesi et al. [120]	-	-	-	-	-	-	-	18.1

Table 6.3: Comparison of footprint dimensions between current and past studies

Studies	Area (mm)			
	SS	IS	TM	SC
Current study	317	361	221	664
Dugas et al. [74]	155	176	222	241

Table 6.4: Comparison of footprint surface areas between current and past studies

6.2.3 Limitations

One of the limitations of this study is the lack of information regarding size of the cadavers. The height and weight might influence the size of the rotator cuff tendons and footprints. The variation in anthropometry could be attributed to the use of Asian cadavers but more extensive studies are required to confirm this due to the limitation in number of specimens used in the current study.

6.3 TENSILE TEST OF ROTATOR CUFF TENDONS

6.3.1 Tensile test

The irregular and complex geometry of the tendons made measuring cross sectional areas for the tensile tests difficult and a previous study has reported similar problems [88]. The cross sectional areas were calculated using an elliptical approximation (width – major axis, thickness - minor axis) but other studies have also used rectangular and square approximations [88, 93, 107]. No slippage or clamp failure occurred during tensile testing, thus the brass wire enclosure gripping technique could be used as a viable alternative to freeze clamping or other gripping techniques.

In the current study, the SS and IS moduli were lower ($p < 0.05$) than those reported by Halder et al. [93] and Itoi et al. [107] whereas the TM moduli were similar (Table 6.5). The lower values observed may be due to the difference in the direction of pull of the tendon in relation to the humeral head. The supraspinatus was pulled at a glenohumeral angle of 90° in Itoi's study while the supraspinatus was pulled at an angle of 0° in the current study. It was reported by Halder that high elastic moduli were observed when pulled at a higher glenohumeral angle. SC, which has not been reported previously, was found to be similar to the SS and IS. Although prevalence of tears in the SC tendon was reported to be around 27% [121], no modulus value was found in the literature. With the complete moduli values of the rotator cuff tendons from the current study, a more comprehensive finite element model can be built.

Studies	E (MPa)		
	IS	TM	SS
Current study	80.54	19.56	69.56
Halder et al. [93]	113	14	-
Itoi et al. [107]	-	-	90

Table 6.5: Comparison of elastic moduli between current and past studies

6.3.2 Limitations

All the cadavers used for this study were Asian males with a mean age of 65 years; this could have contributed to the lower moduli values of the tendons. Previous study on soft tissues concluded that linear stiffness decreases as age increases [122]. Hence, the current results cannot be ascribed to a younger population. The sample size of the supraspinatus tendon for the tensile test was small, since specimens with partial thickness tears were eliminated, this could have affected the statistical distribution of the study. The tendon strips were divided into two strips of equal width; this could have lowered stiffness due to less cross-enforcement of intermingling fibers [93]. No data regarding the weight and height were available to correlate with the determined values.

6.4 FINITE ELEMENT ANALYSIS

6.4.1 Finite element analysis

Compared with Seki et al's [108] results, the maximal tensile stress of the supraspinatus at an elevation angle of 0° for the current model was observed on the same location on the articular side of the anterior edge of the supraspinatus tendon. However, the magnitude was 20% of Seki et al's due to the difference in tendon material properties used. It was noted that maximum tensile stress for all the tendons are located near the insertion sites. Codman stated that rotator cuff tears most often initiate on the articular surface and extend outward until they become full-thickness tears [3]. Matsen further noted that the tears begin near its insertion, close to the long head of the bicep, that is the anterior edge of the supraspinatus [123].

A difference in strain between the articular and bursal surface does not necessarily cause shear stress. From the current model, the reaction force from the humerus creates a transverse force on the tendon, which would have resulted in shear stresses within the tendon. This could be shown from the current FE model, where higher shear stresses were found to be concentrated near the footprint within the supraspinatus (Figure 6.6). Due to the nature of the layered anatomy of the tendons [42], these shear stresses near the footprint could initiate tears, contribute to the propagation of the intratendinous defects, and ultimately result in delamination of the tendons.

Figure 6.6: Shear stresses across the longitudinal section of the supraspinatus

The FE model was validated with the experimental results, both showing similar trend in the strain. Apart from the limitations of the FE model itself, differences in results may also be due to the trough created in the humeral head during the experiments. Various experiments had been conducted to show the difference in strain at the articular and bursal surface of the supraspinatus [9, 17, 81] but it was not possible to observe how the strain changes between the two surfaces experimentally. However, the current FE model is able to predict the variation.

At 60° , it was observed that the strain profile varies linearly across the anterior supraspinatus from positive strain at the articular surface to negative strain at the bursal surface, with the 0% strain locating at two-third of the thickness from the articular surface. At this angle, the supraspinatus is no longer wrapping around the humeral head.

It can be assumed that the shear force away from the footprint is minimal since the load is essentially along the fibres, thus this strain variation resembles that of pure bending in a beam.

With this validated model, the strain profile of the rotator cuff tendons can be predicted at different elevation angles in the scapular plane with various high loadings.

6.4.2 Limitations

Although the present FE model is realistic in geometry, several approximations have been introduced in order to improve the computational performance. First of all, the material properties for the soft and hard tissues were considered to be linear, elastic, homogeneous and isotropic. The humeral head was simplified to a cortical bone shell, without the cancellous bone, subchondral bone and articular cartilage. The calcified fibrocartilage and noncalcified fibrocartilage at the footprint insertion between the tendon and humeral head was also not included in the model. The rotation axis of the humeral head was assumed to be the same and not translated. All of the foregoing simplifications limit the FE model to be an approximate representation rather than a 100% replication of an actual rotator cuff model, but they do not compromise its ability to predict a trend accurately.

7 CONCLUSIONS AND FUTURE WORK

7.1 Conclusions

A novel experiment was developed and conducted to simultaneously measure the strain of the supraspinatus, infraspinatus and subscapularis tendons with the glenohumeral joint intact. Strain measurements at various arm positions, simulated tears and repairs were conducted.

The rotator cuff strains showed varying trends at different arm positions. The strain difference between the articular and bursal side of the supraspinatus implied the occurrence of shearing due to the wrap of the tendon around the humeral head, which may cause intratendinous tears. Strain differential was also observed between the anterior and posterior supraspinatus at the coronal plane at higher elevation angles. A 2mm partial tear at the bursal surface of the anterior supraspinatus increased the strain of the anterior supraspinatus at the articular surface while a full thickness tear at the anterior supraspinatus increased the strain at the posterior supraspinatus. Single-row repairs increased the strain difference between the articular and bursal surfaces of the supraspinatus. It was shown that double-row repairs restored the strains to the intact strain condition and thus may be more efficient for tendon healing than single-row repairs. Due to the higher strain difference and higher stresses within the supraspinatus, elevation of arms at higher angles should be avoided after surgical repair of the tendon.

The footprint area and dimensions of the rotator cuff tendons of 19 Asian shoulder specimens were collected. Tensile tests conducted on the rotator cuff tendons showed that there is no significant difference in the elastic modulus among the supraspinatus, infraspinatus and subscapularis (mean 72.78 MPa). However, the teres minor has much lower mean elastic moduli of 19.56 MPa.

The strain, anatomical data and material properties collected were used in the validation of the three-dimensional finite element model that was developed. The FE model showed similar trends in the strain as compared to the experimental results. High shear stresses were observed near the footprint within the tendons. This proves that the transverse forces from the humeral head are acting on the tendons, resulting in shear stresses that can initiate tears, propagate intratendinous defects and ultimately cause in delamination of the tendons. From the FE model developed, it was observed that the strain varies linearly across the supraspinatus between the articular and bursal surface at elevated angles. At elevated angles, the tendon is no longer wrapping around the tendon. It can be assumed that the shear force away from the footprint is minimal since the load is essentially along the fibres, thus this strain variation resembles that of pure bending in a beam.

7.2 Future work

Future research should be aimed at expanding the number of specimens measured for the anthropometric study and tensile tests. Pneumatic clamps could be utilized to provide a better grip for the tensile tests.

Experimental strain studies could include more tear and repair configurations and also on the rest of the rotator cuff tendons.

Viscoelastic properties of the rotator cuff tendons could be included in the FE model for a more realistic representation, especially at high physiological loads. The cancellous bone, subchondral bone and articular cartilage could be included in the humerus bone. The calcified fibrocartilage and noncalcified fibrocartilage at the footprint insertion between the tendon and humeral head could also be included in the model. Further FE analysis on the rotator cuff tendons could be done with the addition of simulated tears and repair configurations.

7.3 Publications

The publications generated based on this research are listed as follows:

7.3.1 Conferences

1. J.M. Sheng, S.M. Chou, S.H.Tan, D.T.T. Lie, K.S.A. Yew, “Simultaneous Strain Measurements of Rotator Cuff Tendons at Varying Arm Positions and The Effect of Supraspinatus Tear: A Cadaveric Study” Presented in the 13th International Conference of Biomedical engineering, 6-10th December 2008, Singapore
2. J.M. Sheng, S.M. Chou, S.H.Tan, D.T.T. Lie, K.S.A. Yew, “Effects of tears and repairs on supraspinatus strain measurements” Presented in the 6th World Congress of Biomechanics, 1-6 August 2010, Singapore

- 3 J.M. Sheng, S.M. Chou, S.H.Tan, D.T.T. Lie, K.S.A. Yew, “Tensile properties of the anterior and posterior rotator cuff tendons” Presented in the 6th World Congress of Biomechanics, 1-6 August 2010, Singapore

7.3.2 Journals submitted

- 1 J.M. Sheng, S.M. Chou, S.H.Tan, D.T.T. Lie, K.S.A. Yew, “Technical note: A novel method to measure simultaneous strain of rotator cuff tendons using DVRTs with the glenohumeral joint intact”, submitted to Journal of Mechanics in Medicine and Biology
- 2 J.M. Sheng, S.M. Chou, S.H.Tan, D.T.T. Lie, K.S.A. Yew, “Simultaneous Strain Measurements of Rotator Cuff Tendons at Varying Arm Positions”, submitted to Journal of Biomechanical Engineering
- 3 J.M. Sheng, S.M. Chou, S.H.Tan, D.T.T. Lie, K.S.A. Yew, “Measurement of shoulder anterior-posterior laxity in a healthy and young population”, submitted to Journal of Mechanics in Medicine and Biology
- 4 M. Vivek, J.M. Sheng, S.M. Chou, K.S.A. Yew, S.H. Tan, D.T.T. Lie, “A normative anatomic study of the glenohumeral- rotator cuff complex”, submitted to Proceedings of Singapore Healthcare

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Appendix A: Detailed drawings of purpose-built rig

The following diagrams are the detailed drawings of the individual parts and assembly of the rig:

Figure A: Humerus-positioning Arc Frame

Figure B: Internal and External rotator device

Figure C: Fastener of rotator device

Figure D: Base of Arc Frame

Figure E: Vertical Plate

Figure F: Base of Vertical Plate

Figure G: Base of rig with pulley stands

Figure H: Pulley

Figure I: Isometric View of the Purpose-Built Rig

Figure J: Orthographic projection of the Purpose-Built Rig

Appendix B

Microminiature

DVRT®

Differential Variable Reluctance Transducer

Introduction

Ideal for critical linear displacement measurements, the microminiature DVRT® delivers high performance in a tiny package. Advanced materials and electronics have resulted in a rugged, fast, and sensitive instrument capable of submersion in aqueous environments.

Features of our microminiature DVRTs include micron to sub-micron resolution, linear analog output, flat dynamic response to kHz levels, and very low temperature coefficients. Free-sliding transducer cores are extremely lightweight and utilize flexible, elastic, bio-compatible alloys to provide resistance to kinking and permanent deformation.

A range of stroke lengths and specialized, modular attachments have been developed. Longer stroke lengths provide greater linearity DVRTs with nonlinearity as low as $\pm 0.15\%$. This performance, combined with versatility of design allows the microminiature DVRT® to meet the needs of a wide variety of applications.

Miniature "plug and play" signal conditioners provide linear DC output when supplied with unregulated DC power. Multichannel, OEM and digital display systems are also available.

Features & Benefits

- available with sub-micron resolution and long stroke range
- operating temperature to 175 °C
- frequency response up to 20 kHz
- lightweight core will not influence frequency response
- stainless steel and high-performance polymer design suitable for extremely harsh environments
- waterproof, suitable for submersion in corrosive media such as brake fluid and hot saline
- frictionless design suitable for high duty-cycle applications
- easily customized to suit specific application

Applications

- miniature control elements for automotive and robotic systems
- process control for production-line monitoring
- dimensional gauging for quality control applications
- measuring strain and deflection in materials science and civil structures
- linear/angular positioning of optical components
- miniature force, torque, acceleration sensors
- biomedical sensors for measuring strain in bone and soft tissue

Microminiature DVRT® Differential Variable Reluctance Transducer

How it works

Core position is detected by measuring the coils' differential reluctance, using a sine-wave excitation and synchronous demodulator. This differential detection method provides a very sensitive measure of core position while cancelling out temperature effects.

The transducers' coils and flex circuit leads are sealed in vacuum-pumped epoxy, within the stainless-steel case. This provides outstanding environmental resistance. The DVRT® has been successfully employed in harsh applications, including immersion in saline and pressurized oil.

Differential
Variable
Reluctance
Transducer

Electrical Specifications

(with MicroStrain DEMOD-DVRT®)

Linear Stroke Lengths	3, 6 & 9 mm (standard version) 1.5 mm (high resolution version)
Accuracy*	± 1.0 % using straight line ± 0.1 % using polynomial
Sensitivity	2 volts/mm typical
Signal to noise	2000 to 1 (with filter 3 dB down at 800 Hz, standard)
Resolution (0.05% full scale for standard version)	1.5 µm for 3 mm stroke 3.0 µm for 6 mm stroke 4.5 µm for 9 mm stroke 300 nm for high resolution version
Frequency response	7 KHz (unfiltered)
Temp. coeff. offset span	0.0029%/ °C 0.030%/ °C
Hysteresis*	± 1 micron
Repeatability*	± 1 micron

* at constant temperature

Mechanical Specifications

Overall length	11.3 mm for 3 mm stroke 18.7 mm for 6 mm stroke 26.8 mm for 9 mm stroke 11.3 mm for high resolution version
Gauge length	adjustable, 1.5 mm minimum
Outside diameter	1.5 mm (standard version) 1.8 mm (high resolution)
Housing material	smooth stainless steel, 4-40, 6-32 & 8-32 threaded options
Attachment method	stainless steel clamp, screws or barbs
Leadouts	45 cm, multi stranded, shielded, stainless steel reinforced, Teflon insulated
Connector	keyed Lemo 4-pin with polyolefin strain relief
Operating temperature	-55 to 175 °C

Appendix C: Calibration of the DVRTs

Method:

The voltage outputs were collected with the increasing distance between the two barbs on the DVRT. Using the linear regression function with the help of Microsoft Excel, the relationship between the distance between the barbs and the voltage output of each DVRT was determined.

Channel 1				
distance (mm)	voltage (V)			
	1	2	3	average
4.5	4.999	4.999	4.999	4.999
4.8	4.410	4.527	4.467	4.468
6.0	1.131	1.261	1.217	1.203
6.7	-0.804	-0.742	-0.744	-0.763
7.5	-2.954	-2.839	-2.838	-2.877
8.0	-4.354	-4.234	-4.175	-4.254

Channel 2				
distance (mm)	voltage (V)			
	1	2	3	average
5.41	4.972	4.972	4.972	4.972
5.71	4.643	4.588	4.597	4.609
6.41	2.797	2.762	2.854	2.804
6.91	1.449	1.478	1.462	1.463
7.61	-0.655	-0.765	-0.594	-0.671
8.41	-2.917	-3.094	-3.000	-3.004
8.91	-4.321	-4.513	-4.476	-4.437

APPENDIX

Channel 3				
distance (mm)	voltage (V)			
	1	2	3	average
5.99	4.8	4.91	4.902	4.871
6.99	2.267	2.37	2.381	2.339
7.99	-0.568	-0.44	-0.444	-0.484
8.99	-3.406	-3.254	-3.281	-3.314
9.49	-4.762	-4.618	-4.642	-4.674

Channel 4				
distance (mm)	voltage (V)			
	1	2	3	average
5.16	4.831	4.831	4.831	4.831
5.46	4.25	4.329	4.339	4.306
6.36	1.803	1.761	1.866	1.810
7.16	-0.578	-0.612	-0.533	-0.574
8.16	-3.524	-3.388	-3.606	-3.506
8.66	-4.815	-4.896	-4.957	-4.889

Channel 5				
distance (mm)	voltage (V)			
	1	2	3	average
4.49	4.99	4.99	4.99	4.990
4.79	4.603	4.598	4.6	4.600
5.69	2.295	2.29	2.351	2.312
6.49	0.087	0.075	0.084	0.082
7.49	-2.68	-2.655	-2.668	-2.668
8.09	-4.221	-4.144	-4.183	-4.183

APPENDIX

Appendix D: Raw data of strain results* (%)

Elevation angle		0	15	30	45	60
Scapular	SSar ant	0.00	3.24	7.32	9.01	11.23
		<i>0.00</i>	<i>1.95</i>	<i>1.91</i>	<i>2.16</i>	<i>3.90</i>
	SSbur ant	0.00	-0.54	-0.79	-1.15	-2.34
		<i>0.00</i>	<i>0.57</i>	<i>1.27</i>	<i>1.66</i>	<i>2.62</i>
	SSbur pos	0.00	-1.04	-1.39	-2.41	-4.78
		<i>0.00</i>	<i>0.87</i>	<i>0.79</i>	<i>1.30</i>	<i>3.77</i>
	IS	0.00	1.70	1.71	-0.38	-2.74
		<i>0.00</i>	<i>1.16</i>	<i>1.32</i>	<i>2.25</i>	<i>3.25</i>
	SC	0.00	0.66	0.71	-0.14	-2.16
		<i>0.00</i>	<i>1.54</i>	<i>2.11</i>	<i>2.65</i>	<i>2.55</i>
Coronal	SSar ant	0.00	0.11	3.14	5.53	5.36
		<i>0.00</i>	<i>0.41</i>	<i>2.44</i>	<i>5.09</i>	<i>8.04</i>
	SSbur ant	0.00	-0.57	-0.80	-2.00	-5.80
		<i>0.00</i>	<i>0.73</i>	<i>1.97</i>	<i>4.68</i>	<i>7.18</i>
	SSbur pos	0.00	-0.92	-2.92	-6.95	-11.04
		<i>0.00</i>	<i>1.14</i>	<i>2.51</i>	<i>6.71</i>	<i>9.48</i>
	IS	0.00	0.06	0.69	0.47	0.22
		<i>0.00</i>	<i>0.16</i>	<i>1.68</i>	<i>1.93</i>	<i>3.25</i>
	SC	0.00	-0.11	-1.76	-4.83	-7.66
		<i>0.00</i>	<i>0.22</i>	<i>1.56</i>	<i>4.02</i>	<i>6.54</i>
Sagittal	SSar ant	0.00	-0.49	-0.39	-0.78	-2.14
		<i>0.00</i>	<i>1.83</i>	<i>3.90</i>	<i>7.81</i>	<i>10.83</i>
	SSbur ant	0.00	-0.25	-0.34	-1.26	-4.25
		<i>0.00</i>	<i>0.71</i>	<i>1.18</i>	<i>1.54</i>	<i>3.28</i>
	SSbur pos	0.00	-0.35	-0.70	-2.22	-4.72
		<i>0.00</i>	<i>0.64</i>	<i>0.93</i>	<i>2.47</i>	<i>5.33</i>
	IS	0.00	0.28	0.64	0.45	0.40
		<i>0.00</i>	<i>1.69</i>	<i>1.75</i>	<i>1.42</i>	<i>4.24</i>
	SC	0.00	-0.15	-0.24	-0.51	-0.55
		<i>0.00</i>	<i>0.61</i>	<i>1.17</i>	<i>1.46</i>	<i>1.45</i>

APPENDIX

Ant 2mm tear	SSar ant	3.08	4.31	9.09	11.75	13.22
		<i>2.99</i>	<i>4.06</i>	<i>3.17</i>	<i>4.03</i>	<i>5.36</i>
	SSbur ant	0.71	0.03	-0.05	-0.29	-1.54
		<i>1.38</i>	<i>1.33</i>	<i>1.69</i>	<i>2.10</i>	<i>2.14</i>
	SSbur pos	0.64	-0.08	-0.69	-1.60	-3.37
		<i>1.09</i>	<i>1.54</i>	<i>1.88</i>	<i>2.21</i>	<i>4.35</i>
Ant full tear	SSar ant	-0.90	1.64	6.98	11.16	13.29
		<i>2.60</i>	<i>2.61</i>	<i>3.76</i>	<i>4.63</i>	<i>6.67</i>
	SSbur ant	-0.69	-1.34	-1.63	-2.08	-3.15
		<i>3.70</i>	<i>3.94</i>	<i>4.27</i>	<i>4.84</i>	<i>4.82</i>
	SSbur pos	1.08	0.22	-0.07	-0.93	-3.40
		<i>1.03</i>	<i>1.11</i>	<i>1.31</i>	<i>1.85</i>	<i>4.06</i>
Single row repair	SSar ant	3.03	5.71	10.24	12.03	12.62
		<i>4.36</i>	<i>4.30</i>	<i>4.61</i>	<i>3.59</i>	<i>4.54</i>
	SSbur ant	-4.17	-4.85	-5.15	-5.97	-7.29
		<i>4.98</i>	<i>5.36</i>	<i>5.65</i>	<i>6.19</i>	<i>7.38</i>
	SSbur pos	0.77	-0.41	-0.73	-2.16	-3.66
		<i>4.53</i>	<i>5.10</i>	<i>5.35</i>	<i>5.20</i>	<i>5.75</i>
Double row repair	SSar ant	-0.99	1.22	4.95	8.06	9.18
		<i>1.64</i>	<i>2.61</i>	<i>5.16</i>	<i>5.03</i>	<i>4.84</i>
	SSbur ant	-1.79	-2.55	-2.83	-3.15	-5.04
		<i>4.29</i>	<i>4.37</i>	<i>4.46</i>	<i>4.46</i>	<i>5.52</i>
	SSbur pos	2.02	1.06	0.51	0.13	-1.61
		<i>5.96</i>	<i>6.05</i>	<i>6.34</i>	<i>6.35</i>	<i>5.15</i>

Rotation angle		ER30	0	IR30	IR60
	SSar ant	1.04	0.00	-2.49	-5.71
		<i>2.66</i>	<i>0.00</i>	<i>2.92</i>	<i>6.10</i>
	SSabur ant	0.24	0.00	-2.10	-4.56
		<i>2.10</i>	<i>0.00</i>	<i>6.57</i>	<i>8.95</i>
	SSbur pos	-3.57	0.00	0.29	0.48
		<i>3.59</i>	<i>0.00</i>	<i>2.22</i>	<i>2.89</i>
	IS	-1.36	0.00	2.94	4.61
		<i>3.38</i>	<i>0.00</i>	<i>3.67</i>	<i>5.38</i>
	SC	0.89	0.00	-3.69	-9.24
		<i>1.59</i>	<i>0.00</i>	<i>4.48</i>	<i>5.87</i>

APPENDIX

Elevation angle		0	15	30	45	60
FE	SSar ant	0.00	0.41	2.34	4.88	8.75
		<i>0.00</i>	<i>0.02</i>	<i>0.09</i>	<i>0.32</i>	<i>0.71</i>
	SSbr ant	0.00	0.06	-2.30	-4.22	-6.42
		<i>0.00</i>	<i>0.08</i>	<i>0.19</i>	<i>0.32</i>	<i>0.50</i>
	SS br pos	0.00	-0.05	-2.19	-4.59	-7.83
		<i>0.00</i>	<i>0.03</i>	<i>0.28</i>	<i>0.51</i>	<i>0.78</i>
	IS	0.00	-1.52	-3.08	-5.11	-8.22
		<i>0.00</i>	<i>0.16</i>	<i>0.38</i>	<i>0.43</i>	<i>0.30</i>
	SC	0.00	0.23	-0.34	-1.41	-1.90
		<i>0.00</i>	<i>0.07</i>	<i>0.11</i>	<i>0.20</i>	<i>0.26</i>

*Standard deviations are given in italics.