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Modifications in Early Rehabilitation Protocol after Rotator Cuff Repair: EMG Studies

by

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Résumé

La déchirure de la coiffe des rotateurs est une des causes les plus fréquentes de douleur et de dysfonctionnement de l'épaule. La réparation chirurgicale est couramment réalisée chez les patients symptomatiques et de nombreux efforts ont été faits pour améliorer les techniques chirurgicales. Cependant, le taux de re-déchirure est encore élevé ce qui affecte les stratégies de réhabilitation post-opératoire. Les recommandations post-chirurgicales doivent trouver un équilibre optimal entre le repos total afin de protéger le tendon réparé et les activités préconisées afin de restaurer l'amplitude articulaire et la force musculaire. Après une réparation de la coiffe, l'épaule est le plus souvent immobilisée grâce à une écharpe ou une orthèse. Cependant, cette immobilisation limite aussi la mobilité du coude et du poignet. Cette période qui peut durer de 4 à 6 semaines où seuls des mouvements passifs peuvent être réalisés. Ensuite, les patients sont incités à réaliser les exercices actifs assistés et des exercices actifs dans toute la mobilité articulaire pour récupérer respectivement l'amplitude complète de mouvement actif et se préparer aux exercices de résistance réalisés dans la phase suivante de la réadaptation. L'analyse électromyographique des muscles de l'épaule a fourni des évidences scientifiques pour la recommandation de beaucoup d'exercices de réadaptation au cours de cette période. Les activités sollicitant les muscles de la coiffe des rotateurs à moins de 20% de leur activation maximale volontaire sont considérés sécuritaires pour les premières phases de la réhabilitation. À partir de ce concept, l'objectif de cette thèse a été d'évaluer des activités musculaires de l'épaule pendant des mouvements et exercices qui peuvent théoriquement être effectués au cours des premières phases de la réhabilitation. Les trois questions principales de cette thèse sont : 1) Est-ce que la mobilisation du coude et du poignet produisent une grande activité des muscles de la coiffe? 2) Est-ce que les exercices de renforcement musculaire du bras, de l'avant-bras et du torse produisent une grande activité dans les muscles de la coiffe? 3) Au cours d'élévations actives du bras, est-ce que le plan d'élévation affecte l'activité de la coiffe des rotateurs?

Dans notre première étude, nous avons évalué 15 muscles de l'épaule chez 14 sujets sains par électromyographie de surface et intramusculaire. Nos résultats ont montré qu'avec une orthèse d'épaule, les mouvements du coude et du poignet et même quelques exercices de renforcement impliquant ces deux articulations, activent de manière sécuritaire les muscles de la coiffe. Nous avons également introduit des tâches de la vie quotidienne qui peuvent être effectuées en toute sécurité pendant la période d'immobilisation. Ces résultats peuvent aider à modifier la conception d'orthèses de l’épaule. Dans notre deuxième étude, nous avons montré que l'adduction du bras réalisée contre une mousse à faible densité, positionnée pour remplacer le triangle d’une orthèse, produit des activations des muscles de la coiffe sécuritaires. Dans notre troisième étude, nous avons évalué l'électromyographie des muscles de l’épaule pendant les tâches d'élévation du bras chez 8 patients symptomatiques avec la déchirure de coiffe des rotateurs. Nous avons constaté que l'activité du supra-épineux était significativement plus élevée pendant l’abduction que pendant la scaption et la flexion. Ce résultat suggère une séquence de plan d’élévation active pendant la rééducation.

Les résultats présentés dans cette thèse, suggèrent quelques modifications dans les protocoles de réadaptation de l’épaule pendant les 12 premières semaines après la réparation de la coiffe. Ces suggestions fournissent également des évidences scientifiques pour la production d'orthèses plus dynamiques et fonctionnelles à l’articulation de l’épaule.

Mots clés : Épaule, Déchirure de la coiffe des rotateurs, Orthèse d’épaule, Électromyographie intramusculaire, Réadaptation, Immobilisation de l’épaule, Activités des muscles de l’épaule.

Abstract

Rotator cuff tear is one of the most common causes of shoulder pain and dysfunction. The operative repair has been widely performed for symptomatic patients and many efforts have been done to improve the surgical techniques. However, the re-tear rate is still high and this affects post-repair rehabilitation strategies. Post-surgical care should balance between the restriction imposed to protect the repaired tendon and the activities prescribed to restore range of motion and muscle strength. Frequently, early after rotator cuff repair, shoulder is immobilized in a sling or abduction orthosis, but this immobilization includes elbow and wrist joints as well. In this period that may last 4-6 weeks, only passive range of motion exercises are performed. After removing the immobilizer, patients are encouraged to do active assisted and active range of motion exercises respectively to regain the full active range of motion and be prepared for the resistance exercises in the following phase of rehabilitation. Electromyography of shoulder muscles has provided scientific basis for many of rehabilitation exercises during this period. Anecdotally, the activities of less than 20% of the maximal voluntary contraction of rotator cuff muscles are considered safe for the first phases of rehabilitation after rotator cuff repair. Using this concept, the aim of this dissertation is to evaluate the activity of shoulder musculature during some movements and exercises that can theoretically be performed during the early phases of rehabilitation. Three main questions of this thesis are: 1) Do elbow and wrist mobilizations highly activate rotator cuff muscles? 2) Do some resistance exercises of arm, forearm and chest muscles produce high activity in rotator cuff muscles? 3) During active arm elevation, does the plane of elevation affect rotator cuff activity?

In our first study, we evaluated 15 shoulder muscles in 14 healthy subjects with both surface and indwelling EMG. Our results showed that while wearing a shoulder orthosis, elbow and wrist movements and even some resistance training involving these two joints, would minimally activate the rotator cuff muscles and can be considered safe. We also introduced some daily living tasks that can be performed safely during immobilization period. These findings may help to modify the design of current shoulder orthoses. In the second study, we also showed that resisted arm adduction against a low-density foam that replaced the hard wedge of orthosis would not highly activate the cuff muscles. In our final study, we evaluated the EMG of shoulder musculature during arm elevation tasks in 8 symptomatic patients with rotator cuff tears. We found that supraspinatus activity during arm elevation is significantly higher in abduction plane than in scaption and flexion planes in patients with rotator cuff tears. This suggested a plane sequences for active range of motion exercises during rehabilitation.

The findings that are presented in this dissertation, suggest some modifications in the rehabilitation protocols during the first 12 weeks after rotator cuff repair. These suggestions also provide a scientific basis for producing more dynamic and functional shoulder orthoses.

Keywords: Shoulder, rotator cuff tear, shoulder orthosis, Fine wire EMG, rehabilitation, shoulder immobilization, shoulder muscles activity

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List of acronyms

AAROM:	Active Assisted Range Of Motion
ADLs:	Activities of Daily Living
ADM:	Acellular Dermal Matrix
AP:	Action Potential
AROM:	Active Range of Motion
CPM:	Continuous Passive Motion
CSA:	Cross Sectional Area
CT:	Computed Tomography
ECM:	Extra Cellular Matrix
EMG:	ElectroMyoGraphy
ER:	External Rotation
IR:	Internal Rotation
MRI:	Magnetic Resonance Imaging
MU:	Muscle Unit
MUAP:	Motor Unit Action Potential
MVIC:	Maximal Voluntary Isometric Contraction
PROM:	Passive Range of Motion
RC:	Rotator Cuff
RCT:	Randomized Clinical Trial
RCR:	Rotator Cuff Repair
RMS:	Root Mean Square
US:	Ultra Sound

List of abbreviations

d:	Day
e.g.:	exempli gratia, 'for the sake of example'
i.e.:	id est, 'that is'
immob:	Immobilization
w:	Week

Dedication

To my beloved mother, a wonderful woman full of compassion and spirituality….

I wish her soul rest in peace in the garden of heaven.

“You are the universe in ecstatic motion.”

“You were born with wings. You are not meant for crawling, so don't. You have wings. Learn to use them and fly.”

“Your hand opens and closes, opens and closes. If it were always a fist or always stretched open, you would be paralysed. Your deepest presence is in every small contracting and expanding, the two as beautifully balanced and coordinated as birds' wings.”

Jalaleddin Muhammad Rumi

(13th-century Persian Poet and Sufi Mystic)

Acknowledgement

When I landed in Montreal in the summer of 2010, I was very determined to study kinesiology. As a sports physician, I could deeply understand how basic sciences are affecting our way of thinking and clinical approaches. But honestly, I was hesitating to start biomechanics - a field full of physics and mathematics- with my medical background. I was so lucky to meet Prof. Paul Allard, who is not only a great scientist but also a great human being. He introduced me the world of biomechanics, removed my fears, showed me the beauty of this field and helped me step by step to enter in this path. He is my guru in biomechanics, I would never be in this position without him.

My young and energetic supervisor, Mickael Begon taught me all the details, helped me in all aspects of my study and showed me the rights and wrongs in biomechanics. Without his support, I could hardly fulfil my job. When I start working with indwelling EMG, I could not find any expert in Montreal helping me to learn the techniques of electrode insertion. Thanks Rebecca Brookham in the University of Waterloo who shared her experiences with me. But it was Mickael who bravely let me to practice in his own body, helped me build my skills and encouraged me to teach what I learnt to my lab mates. He established a friendly atmosphere in the lab, everybody helped the others, there was always a solution for your problem, and everybody felt happy and satisfied while working hard. He is a great leader, I can easily see a bright future in front of him.

I should thank Dr. Patrice Tétreault, for all his guidance and recommendations. I learnt so many delicate notes in his shoulder clinic in Notre Dame Hospital and he kindly let me to observe his outstanding skills in the operating room. He improved my understanding of shoulder pathologies and showed me how a great surgeon designs his clinical plan. But above all these, I have been impressed by his humbleness, his passion to his patients and his sense of humanity.

I took a lot of positive energy from my enthusiastic colleagues in biomechanics lab. I enjoyed accompanying them in different social activities where I could learn certain French expressions and Québec culture. They assisted me during data collections, and kindly let me to perform medical examination, intramuscular EMG and ultrasonography on their shoulders. I don't know how to express my gratitude. I specially thank Benjamin Michaud and Fabien Dal

Maso, who were always beside me when I was getting stuck in mechanical aspects of biomechanics, and Monique Jackson who helped me with her bright critics and ideas as well as her perfect English edition of the articles.

Lastly, I would like to thank my dear husband for all his supports and encouragement. He worked hard to support the family while he was thousand miles far from our children and me. He accepted this suffering to help us live in a free country, enjoy every moment of freedom and catch the opportunities that were offered to us by this great land. Thanks my dear for all your devotions. I should also thank my two beautiful gifts of god, my dear sons Jalal and Emad. They tolerated a busy mom without nagging and were always sweet and caring. I love you guys with all my heart!

1 INTRODUCTION

Shoulder is a highly mobile joint with a complex joint structure. This high mobility needs a stable base. Unlike hip or knee joints, the glenohumeral joint does not have a deep socket or complex ligamentous structures that keep its stability. Stability of shoulder joint is mostly a function of muscles around the joint which work in a balanced way to press the humeral head into the glenoid. Rotator cuff (RC) muscles play an important role in stabilizing the glenohumeral joint and controlling humeral head translations. They also contribute in glenohumeral abduction, external rotation and internal rotations. It has been of upmost interest to explore the muscles responsible for shoulder stabilization and motions and identify the positions where they are most active. This type of information provided a basis for shoulder muscle training or rehabilitative movements. Although by knowing muscle's origin and insertion and its moment arm, the muscle function can be understood, however, a muscle may be in a good anatomic position for a specific movement, but remains inactive when that motion is performed.[1] Electromyography (EMG) is a generally recognized tool to evaluate muscle activity. EMG provides information on when, how much and how often a muscle is active and evaluates these items throughout a range of motion. It is also a common tool to evaluate the muscle fatigue, a condition that predisposes individual to injury. EMG studies on glenohumeral and scapular muscle activities during numerous shoulder exercises have been commonly the basis of many shoulder rehabilitation protocols including the physical therapy after rotator cuff repair which is the focus of this dissertation.

Rotator cuff tears are among the most frequently encountered causes of pain and dysfunction in the shoulder.[2] Cuff tears are a burden on social and medical resources due to the high number of surgery for rotator cuff repair and long-term rehabilitation pre and post operation. For instance, in 2002, shoulder pain accounted for more than 4.5 million clinical visits in USA that resulted in 40,000 surgical procedures for rotator cuff problems.[3] An annual 75,000 rotator cuff repair with a mean time off work of seven months was also reported.[4] There are similar reports from different countries confirming that rotator cuff tears remain a relevant health problem.[5] Despite the high prevalence of rotator cuff injuries, there are not still clear guidelines for treatments. Most surgeons in the North America regularly prescribe a trial of non-operative treatment such as physical therapy and sub-acromial corticosteroid injection before considering operative repair for chronic types of symptomatic rotator cuff tears.[6] The optimal duration for a non-operative treatment trial has not been clearly delineated. Likewise, evidence in relation to the best protocol for physical therapy is limited. Symptoms duration greater than one year and patient functional disability are considered the poor prognosis factors for non-operative treatment and earlier surgical intervention in these conditions are suggested.[3] Expectations regarding the surgical outcomes vary. While surgeons are often interested in restoring the full ranges of motion and measured muscle strength, patients' main interests are in the relief of pain and restoration of ability to undertake activities of daily living (ADLs), employment, and recreation. A proper physical therapy program as a non-operative treatment or as a complementary treatment after operation has a tremendous importance for achieving the expected goals. The present thesis will concentrate on the early rehabilitation protocols after rotator cuff surgery.

EMG studies during different tasks and exercises have provided valuable information to be applied to shoulder rehabilitation. For example, McCann et al. (1993)[7] quantified the EMG activities of shoulder muscles during the three-phases of shoulder rehabilitation program introduced by Neer (1987)[8] which included passive, active and resistive exercises. They showed that EMG findings were consistent with clinical experience and low muscle activities in the early phases of the rehabilitation program have been reported. Generally, in the early phase after rotator cuff tendon repair, the patients are advised to avoid exercises that generate high rotator cuff activity. To protect the healing tendon, patient's shoulder is immobilized for 4-6 weeks in a sling or a shoulder orthosis and only supervised passive movements are allowed. It has been shown that the activity of cuff muscles was minimal during self-assisted or helper-assisted elevation exercises.[9] Limitation in dynamic rehabilitation is due to high rate of re-tear after rotator cuff surgery[10-12]. It is assumed that higher activity of cuff muscles may stress the healing tissues. However, in this phase of rehabilitation, exercises that activate scapular and other shoulder muscles with minimal cuff activity may be appropriate. For example, an EMG study by Smith et al. (2006)[13] suggested that during periods of shoulder immobilization scapular depression and protraction exercises could potentially be safely performed to facilitate scapula-thoracic rehabilitation. Patients usually start active assisted or active movements from the seventh week post operation. In this period, the plane and angle of elevations as well as arm rotations should be wisely chosen to control the stress level on the newly healing tendon. During more advanced phases of rotator cuff rehabilitation, exercises that produce moderate to higher levels of rotator cuff activity may be employed to help strengthening the cuff muscles who might become weakened or atrophied after a period of disuse.[14] The studies that are presented in this dissertation are mainly related to the immobilization period and the phase of starting active range of motion exercises.

One of the important areas in post-op rehabilitation that should be addressed is the effect of long term tear on the RC muscles. Following rotator cuff tears and musculotendinous retraction induced by tendon release, serious changes such as fatty infiltration, degeneration and muscle atrophy may happen within the rotator cuff muscles.[15,16] Studies on sheep models suggested that fatty infiltration and muscle atrophy progress steadily over the first 16 weeks following tendon detachment.[17,15] As a majority of rotator cuff surgeries are performed on chronic tears, most patients already have advanced levels of muscle atrophy. Post-operative immobilization may even further the muscles atrophy.[18] Therefore, post-op activity level is an important treatment component that needs to receive more attention for the shoulder. One of the main ideas that is followed in this dissertation is, what if full immobilisation condition changes to a semi-immobilization with a dynamic orthosis. Actually, when we started our studies, Médicus Company in Quebec was interested in developing a dynamic shoulder orthosis. Our findings provides a basis for manufacturing such dynamic orthoses.

Theoretically, the amount and pattern of mechanical loading on tendon tissue is important for tendon development and homeostasis. As natural tendon healing is insufficient, manipulation of the mechanical environment of healing tendon may exert a biologic effect for promoting a repair process that restores normal tendon structure and function.[19] Disuse following immobilization has been associated with alterations in tenocyte morphology and loss of normal extracellular matrix (ECM) architecture, resulting in impaired function and healing capacity in animal tendon tissue.[20] An ideal exercise program should provide a biologic stimulus to maintain tendon homeostasis and function while avoiding harmful stress. A meta-analysis study on immobilization after rotator cuff repair suggested that there is not enough evidence indicating that immobilization after repair is superior to early-motion rehabilitation in terms of tendon healing or clinical outcome.[21] Functional impairment in patients with rotator cuff tears may be due to muscle atrophy and weakness. According to this meta-analysis[21], all patients in different studies regained their range of motion 1 year postoperatively, but in early-motion rehabilitation protocol, a significant difference in external rotation at 6 months postoperatively favoured early motion over immobilization. Besides the controversy regarding shoulder full immobilization or early motion, there is an ambiguity regarding the extent of upper limb immobilization, i.e. whether all parts of upper limb including elbow and wrist joints need to be immobilized. Only 4 weeks of elbow immobilization has been shown that significantly decreased the forces of elbow flexors.[22] Early restoration of functional ability of the upper limb is the goal of treatment and is sometimes crucial for patients who are manual workers or professional athletes. This issue is addressed in our studies.

The general aim of this thesis is to study EMG activity of rotator cuff and some other shoulder muscles during certain exercises and daily living tasks to suggest different modifications to the commonly used rehabilitation protocols. Ideally the exercises that minimally activate rotator cuff muscles can be considered safe in early phases after rotator cuff repair. So, the EMG of shoulder musculature are evaluated in the following situations:

- Active elbow and wrist movements
- Some daily living tasks that involve elbow, wrist and fingers movements
- Some resistance exercises with light weights for elbow and wrist
- Arm adduction exercises when active assisted exercises are allowed to be performed.
- Active arm elevation in different planes and arcs of elevation

In the first part of **chapter 2**, the characteristics of rotator cuff tears, and their treatment strategies are elaborated. In part 2.2 the rationales behind rehabilitation protocols and the concept of tendon healing are explained. The readers who are familiar with rotator cuff tears and their management may find this two section a little bit boring but for those who have limited information about this medical problem, reading of section 2.1 and 2.2 is highly recommended. In part 2.3 the basic and clinical studies on upper limb immobilization after rotator cuff repairs are summarized in two synthetic tables to present the current knowledge about the immobilization protocols. In section 2.4, the basis of EMG is explained and the reader can understand how EMG can be used as a tool to identify the safety of different rehabilitation exercises. Considering high number of papers using EMG for evaluation of muscle activity, the strong points and the limitations in using EMG are also elaborated. The methods we used in our biomechanics lab for intramuscular EMG are introduced in details in Appendix 2 to guide future researchers who are interested to work in this field. In **chapter 3** the EMG activity of shoulder muscles during different movements are evaluated and certain types of movement are presented in three articles. The first article entitled "Electromyographic activity in the immobilized shoulder musculature during ipsilateral elbow, wrist and finger movements while wearing a shoulder orthosis" assesses the effect of elbow, wrist and hand mobilization on rotator cuff muscles activity. This article suggests the utilisation of a dynamic shoulder orthosis instead of traditional ones in order to increase the functionality of upper limb while imposing a safe level of load on the repaired tendon. The second article entitled "Electromyographic activity in the shoulder musculature during resistance training exercises of the ipsilateral upper limb while wearing a shoulder orthosis" introduces some resistive training exercises for early post repair period that can induce minimum level of activity within rotator cuff muscles. It also suggests another modification to common shoulder orthosis in the wedge part, using foams with different densities. Both articles have been published in the Journal of Shoulder and Elbow Surgery. The third article: "The effects of elevation plane and angle on EMG activity of shoulder musculature in patients with rotator cuff tears" intends to show how elevation plane and angle can change the pattern of muscle activity during the active arm elevation in patients with cuff tears. This type of exercises is usually prescribed for the patients 4-6 weeks post-surgery, in the second phase of rehabilitation. The latter study has been performed on symptomatic patients with rotator cuff tears who were in the waiting list for surgical repair. Considering that the studies on patient population are very few, this study can specifically demonstrate how the position of arm elevation in this patient group affect muscle activity pattern and introduces some suggestions for this type of exercises. The precise kinematic measurement which has been fulfilled by a 3D motion analysis system and the synchronization of kinematic study with EMG analysis are the strong points of this study which has been published by the journal of Clinical Biomechanics. In **chapter 4** the specific objectives of this dissertation are elaborated and discussed and finally in the conclusion part, some modifications to the commonly used rehabilitation protocols based on our findings are suggested. It is believed that these findings can provide a scientific basis for designing more functional shoulder orthoses and presenting some new exercises for the early periods after rotator cuff repairs.

2 LITERATURE REVIEW

2.1 ROTATOR CUFF TEARS

Rotator cuff tears are a common health problem. Estimates for the prevalence of tears vary widely and might differ according to the age, composition of the community or industry of the area. Lehman, et al. (1994) [23] estimated the prevalence of 6-30% of rotator cuff tears based on their cadaveric study. Ultrasonography studies during a community health check-up for general population in Japan [24] elucidated that 21.7% of 1,328 shoulders had full-thickness rotator cuff tears. This study has been supported by Yamamoto, et al.(2010) [25] who also showed that rotator cuff tear afflicts about 20% of the population regardless of the presence or absence of symptoms. Other Imaging studies reveal that 54% of asymptomatic persons over 60 years of age [26] and 65% of asymptomatic persons over 70 years of age [27] have rotator cuff defects. Massive tears account for 10-40% of all tears.[5] Despite different reports of rotator cuff tear prevalence, all studies agree that the prevalence increases with age and its associated morbidity, in terms of pain and loss of function, can be severely debilitating.

Risk factors that may lead to rotator cuff tears are largely unknown. Some studies have identified increased age as the main risk factor and tears are being regarded as a normal consequence of the ageing process.[27] History of trauma and the dominant arm were also reported as the main risk factors for cuff tear in general population.[25] Increased adiposity[28], arterial hypertension[29] and smoking habit[30] may also contribute to progression of rotator cuff tears. The contribution of genetic factors was suggested by Harvie, et al. (2004) [31] who identified a significantly increased risk of tears in the siblings of patients with symptomatic tears, but this concept has not been supported by further studies. Specific professions such as construction workers, office workers and musicians seem to be at higher risk for shoulder disease due to repetitive uses of the arm and working above shoulder height.[32] People participating in overhead sports activities are more prone to shoulder injuries,[33] because, the repetitive microtraumatic stresses placed on the athlete's shoulder joint complex during the throwing motion may challenge the physiologic limits of the surrounding tissues including rotator cuff musculature.[34] Finally, as mentioned before trauma is an important risk factor for rotator cuff tears and more than 40% of patients may report it in the history before their shoulder problems occurred.[35]

It can be seen that many factors are contributing in development of rotator cuff tears. Tears may not have a single cause but a single or multiple causal chains that may involve biological, environmental or professional risk factors. It is not clear how these risk factors work together and the magnitude of each factor on development of tear is not clear. By far, age is the most important factor for tear progression. Some of these risk factors are modifiable, some are not. Clinical studies mostly manipulate the modifiable risk factors and provide evidence for clinical approaches. However, they do little to increase our understanding of the nature of rotator cuff muscles. Basic science studies by explaining the nature and special characteristics of rotator cuff muscles and tendon can guide preventive or therapeutic interventions to be optimally timed and progressed. This dissertation presents some basic science studies to provide a basis for rehabilitation protocols in the early post-repair period.

2.1.1 **Etiology of rotator cuff tears**

With the exception of acute injuries leading to rotator cuff tears, it is generally believed that chronic impingement and tendinopathy can lead to partial tears that progress to full-thickness tears over time.[36] Neer (1983)[36] hypothesized that the mechanical compression and abrasion of the cuff tendons result from mechanical compression by some structure external to the tendon such as abnormal acromial morphology. These "*extrinsic* factors" were viewed as the main initiating factors leading to dysfunction of the rotator cuff and eventual tearing. The term "subacromial impingement" has been used to describe irritation from the antero-inferior aspect of the acromion onto the superior aspect of the rotator cuff. The subacromial space is defined by the humeral head inferiorly, the anterior edge and under surface of the anterior third of the acromion, coracoacromial ligament and the acromioclavicular joint superiorly (Figure 1). Theoretically, when the arm is elevated, the humeral head and the acromion approach each other and narrowing the subacromial space.[37] Faulty posture, altered scapular or glenohumeral kinematics, posterior capsular tightness, and acromial or coracoacromial arch pathology are among the potential extrinsic mechanics that may lead to impingement. Subacromial decompression or acromioplasty is a popular operative approach attempting to alter presumed aberrant acromial morphology, and therefore eliminate impingement on rotator cuff.

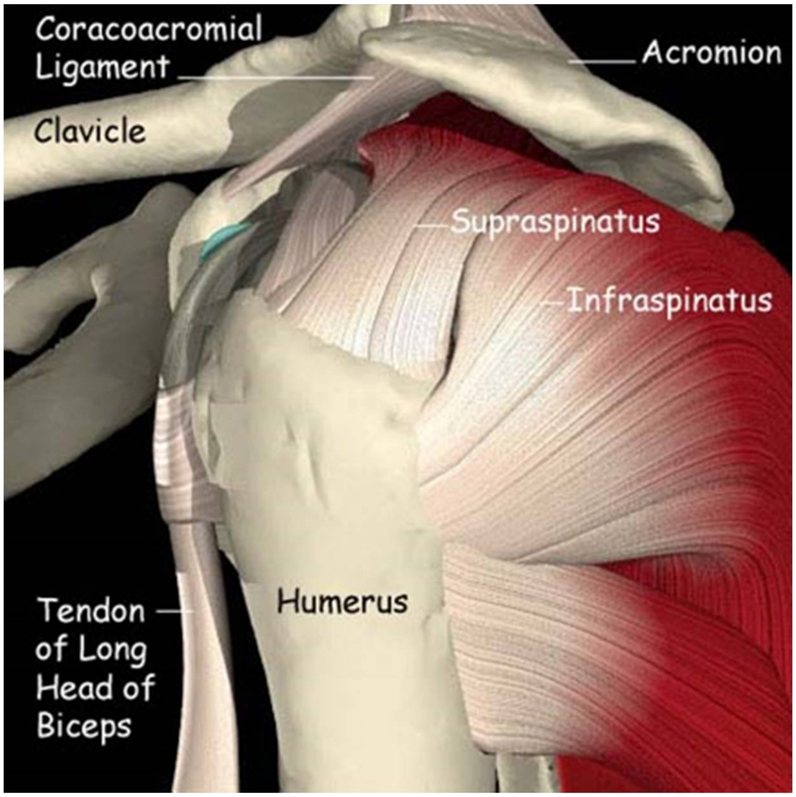

Figure 1: Subacromial space

Inferior: humeral head, superior: under surface of the anterior third of the acromion, coracoacromial ligament and the acromioclavicular joint.

Figure is taken from:

[*http://thelondonshoulderpartnership.co.uk/shoulderinformation/shoulder/shoulder-impingement*](http://thelondonshoulderpartnership.co.uk/shoulderinformation/shoulder/shoulder-impingement)

However, other evidence suggested that, in most patients who have an abnormality of the rotator cuff, the primary problem is intrinsic. The *'intrinsic impingement'*, theorizes that partial or full thickness tendon tears occur as a result of the degenerative process that occurs over time with overuse, tension overload, or trauma of the tendons.[38,39] Subsequently the osteophytes formation, acromial changes, muscle imbalances and weakness, and altered kinematics will follow leading to secondary subacromial impingement. However as the usual clinical examination findings reveal both tendon pathology as well as one or more extrinsic factors such as osteophytes or muscle weakness, it is not clear which form comes first, tendon degeneration or changes external to the tendon? However, the orthopaedic and rehabilitation approaches mainly address the extrinsic factors because tendon degeneration has not been very well understood and so its controlling factors have not been clearly determined. I briefly explain what we know about tendon degeneration. Understanding of this issue is important because all the rationales behind the rehabilitation protocols are related to tendon pathology and healing process.

Basic science researchers tried to explain tendon degeneration. Vascular studies have described the presence of a "critical zone" in the rotator cuff, corresponded to the zone of the anastomoses between the osseous and tendinous vessels [40] or about 1 cm proximal to the insertion of the supraspinatus tendon into the humeral head.[41] Cadaveric studies suggested a hypovascularity in the critical zone, and presumed hypoperfusion within this area might result in degeneration and ultimately failure of the tendon. However other vascular studies have produced contradictory findings, and histologic analysis of surgical biopsy specimens of torn rotator cuff tendon showed vascular proliferation in the biopsy specimens.[42,39] Analysis by intraoperative laser doppler flowmetry [43] has also shown blood flow throughout the entire rotator cuff including hyperaemic response at the edge of the tear. Despite the controversy regarding the existence of this critical zone, we will see later that critical zone is commonly mentioned in the clinical literature. For example it is suggested that after cuff repair, immobilization in abduction position can provide better blood supply to that critical zone.[44]

Other basic-science researches have been directed toward cellular studies emphasising the importance of intrinsic factors. Kannus and Józsa (1991)[45] evaluated the specimens obtained from the biopsy of spontaneously ruptured tendons in 891 patients and noted degenerative changes in 97% of cases. Likewise, Hashimoto et al. (2003)[46] observed a high prevalence and diffuse distribution of degenerative changes in torn rotator cuff tendons without any distinct inflammatory reaction. But it was Matthews et al. (2006)[47] who distinct the inflammatory process from the degenerative process in their biopsy samples of supraspinatus tendon in 40 patients with chronic rotator cuff tears. They observed that small sized tears had increased fibroblast cellularity and intimal hyperplasia, together with increased expression of leucocyte and vascular markers, retaining the greatest potential to heal. On the contrary, large and massive tears showed marked oedema and degeneration with no increase in the number of inflammatory cells and blood vessels. These findings could explain why stiffness is more prevalent in small tears where higher activity of inflammatory process exists and why large degenerated tears have less capacity of healing and therefore, are more prone to re-tear.

In conclusion, the exact pathogenesis of rotator cuff tears remains unclear. It is probable that the cause of tendon pathology is multifactorial which involves extrinsic impingement from structure surrounding the cuff and intrinsic degeneration within the tendon. Generally, the degeneration - microtrauma theory is the most accepted theory for explanation of rotator cuff diseases. Age-related degeneration, vascular changes, and inflammation are all potential contributors to the intrinsic pathology of the rotator cuff. The histopathologic changes leading to rotator cuff rupture are gradual and progressive. However the exact pathway of these changes and the order of sequences are not exactly known. All these ambiguities result in difficulty of addressing the main causative factors and designing a proper preventive or therapeutic plan for rotator cuff tears. So, it is important to understand that in this dissertation we will not target the causative factors but some external factors (such as immobilization and exercises) that may affect the tendon healing are discussed.

2.1.2 Normal Tendon

Rotator cuff consists of the tendons of the subscapularis, supraspinatus, infraspinatus, and teres minor muscles. The normal tendon of the rotator cuff has the average thickness of 10 to 12 mm.[48] It is formed by the confluence of tendon, the joint capsule, the ligaments (coracohumeral and glenohumeral), all of which blend before inserting onto the humeral tuberosities. The supraspinatus and infraspinatus are not really separated and join proximal to their insertion.[49] Clark and Harryman (1992)[50] performed a histological analysis of the rotator cuff insertion and defined five distinct histological zones in the supraspinatus and infraspinatus portions of the rotator cuff. Figure 2 demonstrates those layers. It should be noticed that the roof of the biceps sheath is formed by fibers from layer II of the supraspinatus. A group of bundles from the subscapularis joins with fibers of the supraspinatus to serve as the floor of the biceps sheath. The rotator cuff, the coracohumeral ligament complex, and the bicipital sheath are intimately interconnected. This anatomical characteristic may help to understand why biceps pathology commonly occurs following evolvement of the tear.

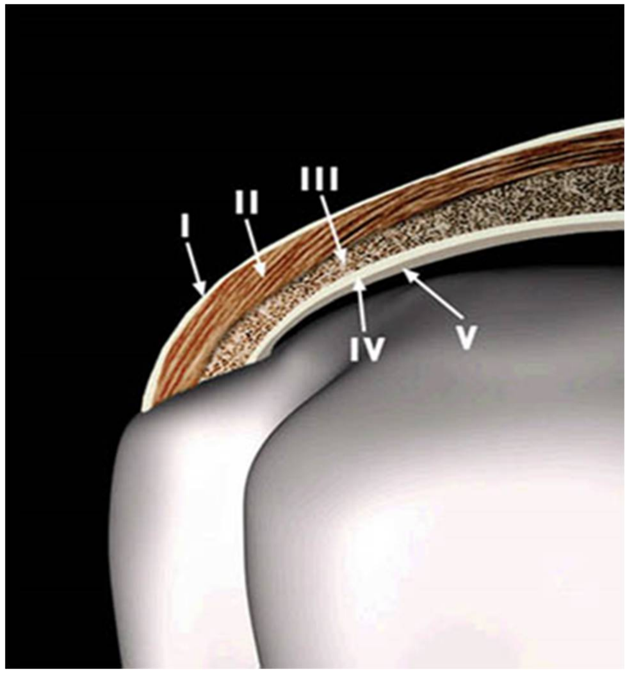

Figure 2: Histological layers of the cuff

Layer 1: 1 mm in thickness, the most superficial layer, contains large arterioles and composed of fibers from the coraco-humeral ligament, Layer II: 3-5 mm in thickness, large bundles densely packed fibers that parallel the long axis of the tendon, representing the direct tendinous insertion into the tuberosities, Layer III: 3 mm thickness, smaller bundles of collagen with a less uniform orientation, loosely organized fibers forming an interdigitating meshwork, Layer IV: loose connective tissue and thick collagen bands that merges with fibers from the coraco-humeral ligament Layer V: 2 mm in thickness, the shoulder capsule, comprises a sheet of interwoven collagen extending from the glenoid labrum to the humerus.

Figure derived with permission from: www.radsource.com

The insertion site of the rotator cuff tendon is often referred to as the footprint. According to the cadaveric study of Curtis et al. (2006),[49] each rotator cuff tendon has its own, unique and measurable insertion onto the humerus. (Figure 3).

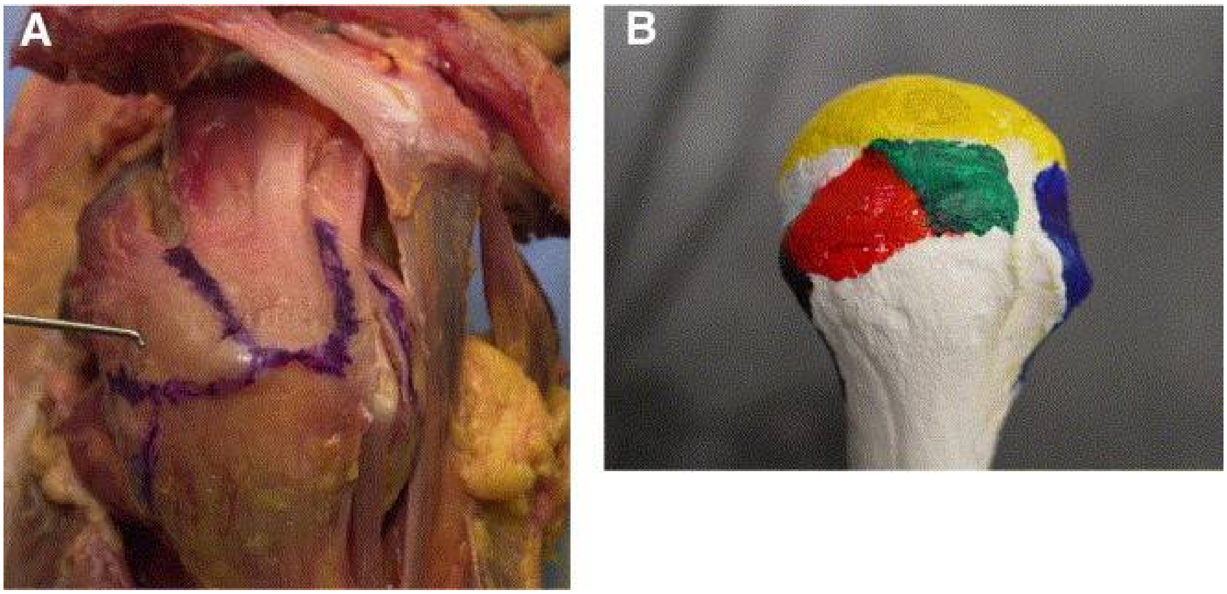

Figure 3: Rotator Cuff Footprint

A: intact myotendinous unit, B: supraspinatus footprint (green), infraspinatus footprint (red), subscapularis footprint (blue) and teres minor footprint (black).

Figure copied from the article written by Curtis et al.[49] The permission was taken from Dr. Alan Curtis the corresponding author (in Boston Sports & Shoulder center)

The supraspinatus portion of the cuff inserts and covers the antero-superior aspect of the greater tuberosity adjacent to the articular cartilage of humeral head. Infraspinatus and teres minor are slightly away of the articular margin and create a bare area. Restoration of anatomical footprint for torn tendon is critical for surgical outcomes. Knowledge of anatomical footprint have influenced on surgical techniques aiming to increase the available surface area for repair.[51] Surgical repair is more difficult for chronic tears with degeneration and muscle retraction than acute tears. In retracted situation, more tension is required to reattach the torn tendon. To protect the newly repaired tendon, the tension level should be also adjusted post-surgery and proper arm positioning in the immobilization period may help in repair integrity. This issue will be discussed in the next sections and is one of the major topics of the present thesis.

2.1.3 **Tears in Different Views**

Different methods of tear classification are presented in Appendix 1. This section will present some common approaches for tear definition.

2.1.3.1 Partial *vs* Full Thickness Tear

A *partial-thickness tear* is considered to be a definite disruption of the fibres of the tendon not fraying or softening of the surface and occur within the tendon without communicating with the subacromial bursa or the glenohumeral joint. The degree of tearing is described more by the depth involved in the thickness of the tendon than by the area of the tear. partial thickness tears have 3 subtypes:[48]

1) *Bursal-sided tear*: less common but frequently the most symptomatic.

2) *Intratendinous tear:* occurs between the superficial and deep layers of the tendon, may present as a cystic collection in the muscle.

3) *Articular sided tear*: 2-3 times more frequent and more symptomatic than bursal surface tears and frequently occur near the supraspinatus tendon-bone interface.

In tears of the bursal surface, subacromial impingement may be responsible. Intratendinous lesions may occur in the presence of differential shear stress between the superficial and deep surface layers of the tendon and articular sided tears are mostly because of trauma to a degenerated tendon.[52]

With *full thickness tears*, the entire tendon has separated or torn from the bone. Full thickness tears can initiate on the anterior, posterior or middle portion along the width of the tendon. In almost 90% of cases, the tear is located in the anterior portion.[53] A transverse tear exposes the insertion side but a longitudinal tear occurs along the torn tendon fiber. Full thickness tear can be small pinpoint, larger button hole, or involve the majority of the tendon where the tendon still remains substantially attached to the humeral head. Full thickness tears may also involve complete detachment of the tendon(s) from the humeral head and may result in significantly impaired shoulder motion and function.

Massive Tear is usually defined as a tear of greater than five centimeters in diameter or in terms of the amount of tendon that has been detached from the tuberosities. There is no universal agreement on the definition of a massive rotator cuff tear, however, some common definitions can be found in Appendix 1. Most massive tears involve supraspinatus and infraspinatus, but anterosuperior tears involving supraspinatus and subscapularis are also moderately common.[54]

2.1.3.2 Symptomatic *vs* Asymptomatic

The clinical manifestations of rotator-cuff tears vary widely among patients. It seems that there is no correlation between tears and symptoms as research studies have demonstrated substantial numbers of people with asymptomatic shoulders and full function have partial or full thickness rotator cuff tendon tears.[25,55,56] There is considerable uncertainty why the presence of a structural full thickness tear of the rotator cuff may be associated with disabling pain and loss of function in some individuals and be asymptomatic in others. Yamaguchi et al. (2000)[57] found that 40% of patients with symptomatic rotator cuff tears had also an asymptomatic tear in the contralateral shoulder. Interestingly the symptomatic tears were on average 30% larger than asymptomatic ones. The mechanism behind the evolution of pain in the setting of rotator cuff pathology is unclear. If we assume that the patient's pain is related to his cuff tear, then it is expected that a longer duration of symptoms should correlate with a larger tear size, more muscle atrophy, and poorer active motion. However there is evidence suggesting that the severity of pain does not correlate with the severity of rotator cuff disease.[58,59] These observations cast doubt on the assumption that rotator cuff tears are the source of a patient's symptoms and suggest that pain in this patient population may be originating from other sources. The study of Flurin et al. (2007) [60] who assessed cuff integrity after arthroscopic rotator cuff repair somehow confirmed this idea. According to their study, all of the components of the Constant score were dramatically improved by surgery but better functional results in terms of activity, motion, and especially strength were obtained when the cuff remained intact on postoperative imaging studies. Interestingly, the Constant sub score for pain did not correlate with the anatomic results. Likewise, Dunn et al.(2014)[59] in their multicenter study on 393 patients could not find any significant relationship between pain and the severity of the cuff disease (e.g., number of tendons torn, degree of retraction, and degree of fatty degeneration). In contrast, increased comorbidities, lower education level, and race were significantly associated with pain on presentation.

Moreover, the exact tear size that causes a loss of normal shoulder biomechanics is unknown. Why some patients with rotator cuff tear have still normal function? Burkhart et al. (1993) [61] described the theory of "rotator cable-crescent complex" in an attempt to explain this issue. According to this theory the intact rotator cuff inserts anteriorly on the greater tuberosity of humerus, and posteriorly closes to the inferior border of infraspinatus, so it acts like a "suspension bridge". At the margin of avascular zone, the arching cable like thickening of the coraco-humeral ligament is located. Stress on the muscles is transferred to this cable and in case of tear, the free margin of tear corresponds to the rotator cable but the anterior and posterior margins correspond to the supports at the each ends of cable span. Therefore even in the case of damage to supraspinatus, the compressive effect of the tendon can be exerted on the humeral head through distributing tensions along the suspension bridge. Ludewig et al. (2009)[62] in their 3D kinematic study demonstrated that during all humerothoracic elevation motions, glenohumeral external rotation occurred irrespective of plane. They suggested that as the tears progress into the posterior part of the rotator cuff (infraspinatus) and the patients lose external rotation strength, then the functional lose is more pronounced. These explanations can somehow clear why some patients with rotator cuff tear still have arm elevation. However, harmonizing the study population in respective to tear size or intensity of the symptoms is very challenging and two patients with similar tear characteristics may have different pain or functional scores. This issue will be demonstrated and deliberated in our third article (section 3.3).

Patients with acute, traumatic cuff tears may experience the sudden onset of weakness with elevation of the arm after an injury while symptomatic patients with chronic degenerative cuff defects may notice a gradual onset of shoulder weakness and pain, reduced functional ability including an inability to dress, attend to personal hygiene and use utensils to eat. They may also complain of nocturnal pain that affects their sleep.[63,64] However, as mentioned before many degenerative rotator cuff defects are asymptomatic. It has been estimated that more than half of asymptomatic tears become symptomatic in around 3 years.[65,66]

It is important to consider that all surgical treatment and rehabilitation protocols are planned for symptomatic patients, not for anatomical tear. It is the patient who should be treated not the tear! Therefore, when designing a rehabilitation program, it is important to address the patient's expectations. Patients usually desire to do their daily living activities and return to a normal life as soon as possible, while clinicians may aim to restore the full range of motion and measurable cuff strength in a gradual process. So in this thesis both of these expectations are considered.

2.1.3.3 Acute vs Chronic

Acute tears are reported to make up 8% of all rotator cuff tears and are usually related to a trauma or shoulder dislocation.[67] Traumatic tears are caused by a fall or trauma to an abducted externally rotated arm. They usually occur in individuals, with a mean age younger than the population affected by chronic cuff tears. Traumatic tears tend to be larger in size and also can involve the subscapularis tendon. In fact, in 50% of the cases, they are large or massive tears.[65] It should be noticed that the definition of an acute tear is not always easy. Many patients report an acute event that initiated their symptoms, but many of these acute events were potentially a new injury to a shoulder that already had a rotator cuff tear. Determining if the rotator cuff tear is acute may be clinically challenging and usually requires additional investigation tools such as MRI to evaluate fatty degeneration, atrophy, and retraction.[67]

Chronic tears are the consequences of gradual and progressive histological changes due to extrinsic or intrinsic contributing factors which have been discussed in the previous sections.

2.1.3.4 Uni vs Multiple tendon

By far, supraspinatus is the most tendon involved; In a study with resonance magnetic arthrography, 93 cases of 105 partial thickness rotator cuff tears, and 43 cases of 93 full thickness rotator cuff tears were in supraspinatus.[68] It is believed that the tear typically starts from anterior portion of supraspinatus humeral insertion near the long head of biceps and propagate posteriorly.[69] However, in an ultrasound study by Kim et al. 2010,[70] it was suggested that lesion arose in region 13-17 mm posterior to the long head of biceps tendon, near the junction of supraspinatus and infraspinatus tendons. Infraspinatus tear was reported in the second place with 60.4% of the cases.[53] Teres Minor tear is often associated with supraspinatus and infraspinatus tears (SIT tears) following a degenerative process.[71] Rupture of the subscapularis tendon is rare and the incidence was reported as 4-8%.[11] Mechanism is often an acute avulsion in younger patients with a hyperabduction / external rotation injury. The injury can be an isolated rupture or it may be combined with rupture of the supraspinatus.[11] Considering the higher frequency of supraspinatus tear, the activity of the supraspinatus and its rehabilitation is more discussed in this dissertation.

2.1.4 Treatment: Conservative or Operative

Treatment for rotator cuff tendon disease ranges from conservative treatment to surgery. The decision how to treat a rotator cuff tear is based on the symptoms and its duration, examination findings, tear sizes, co-morbidities, the type and duration of previous treatment and available evidence about outcome. Most symptomatic rotator cuff injuries may be treated conservatively by using nonsteroidal anti-inflammatory drugs, corticosteroid injections, acupuncture, physiotherapy, manual therapy or functional rehabilitation. Most surgeons consider surgery after a period of failed conservative treatment. However the type and duration of this conservative treatment vary and the decision to operate is not as straightforward as it might be thought. Two review studies have highlighted this difficulty. Dunn et al. (2005)[6] selected a list of orthopaedic surgeons from American Academy of Orthopaedic Surgeons directory and characterized their attitudes concerning medical decision-making about rotator cuff surgery and investigated the associations between these beliefs and reported surgical volumes. They found significant variation in surgical decision-making and a lack of clinical agreement among orthopaedic surgeons about rotator cuff surgery. Oh et al. (2007),[3] in their systematic review investigated the influencing factors on decision making for rotator cuff operation. In this extensive study, they evaluated different variables such as demographic characteristics, symptoms duration, tear characteristics, indications for surgery and surgical outcomes. The conclusion of this review was that the exact indications for repair are not clear and further researches are needed to answer the question as when to operate on the rotator cuff. Therefore, the approach to the management of cuff lesions is largely based on physician's preference and their clinical experience. The general trend is as follows:

2.1.4.1 Acute Complete Tears

Acute rotator cuff tears even if they are massive are often good candidates for repair as long as the tissue compliance is well maintained.[69] It is generally accepted that full-thickness rotator cuff tears will not heal spontaneously, consequently, prolonged observation and nonsurgical management allow the detached tendon to retract and resorb[72] while the muscle atrophies and fatty degeneration ensues[17] which in some individuals can lead to an irreparable tear. In a retrospective series,[73] it was reported that tears that were repaired within the first 3 weeks of an acute injury had a greater return of motion (abduction) than those repaired after 3 to 6 weeks and those repaired from 6 to 12 weeks.

2.1.4.2 Partial-Thickness Rotator-Cuff Tendon Defects

Most partial thickness tears are treated conservatively. However, spontaneous healing of partial-thickness tears is unlikely,[42,52,74] because the torn ends should contact and a good blood supply is needed. Then what is the rationale behind conservative treatment?
Fukuda et al.(2003)[48] presented a modification version to Neer's staging (see Appendix 1) which is more directly related to treatment options. They proposed that both acute oedema and haemorrhage, and chronic fibrosis and tendinitis belong in 'modified' stage I, with a full-thickness tear in a 'modified' stage III. They believe that all stage (modified)-I lesions are better to be treated conservatively. For those in stage (modified) II with partial thickness tears, if the signs and symptoms of inflammation are alleviated, and if mechanical defect of the torn tendon compensated by prime movers and intact part of cuff muscles, then a clinical 'cure' is achieved. Fortunately the part of the tendon remaining intact prevents retraction and muscle atrophy.[69] Patients in whom the symptoms of a partial cuff tear are refractory to the conservative treatment may benefit from surgery. Some believe that the choice of treatment depends on the exact cause of lesion and the treatment should be directed towards a primary diagnosis such as impingement syndrome or instability.[75] By this way, treatment of tear itself is considered secondarily.

2.1.4.3 Chronic, Full-Thickness, Degenerative Tendon Defects

While urgent repair for an acute traumatic cuff tear is mostly agreed, for treatment of atraumatic cuff tear, there is not a consensus. Full thickness tears likely progress over time with retraction of the tendon edge, which may lead to an irreparable tear. Healing is potentially hindered because of poor vascularization in certain regions as well as the intra-articular environment, in which synovial fluid may interfere with healing.[67] As these tears often are considerably chronic, the physicians usually try a substantial period of non-operative management to improve the mechanical dysfunction such as lack of motion or stability.[69] Nonsurgical approaches include pain management, activity modification, and gentle stretching and strengthening exercises for the muscles that remain intact. Although there are not enough randomized clinical trials to assess the benefits of exercise therapy for full thickness degenerative defects, other studies such as case series or case reports have shown improvement in patients' symptoms with exercise.[76,77] However, some clinicians believe that surgical treatment is the only option for symptomatic patients with full-thickness rotator cuff tear.[48]

Bartolozzi et al. (1994)[78] recommended that early surgery to be considered in a full-thickness tear greater than or equal to 1 cm^2, symptoms lasting longer than 1 year, and functional impairment and weakness. However, Unruh et al. (2014)[58] in their prospective cohort study on 450 patients with full-thickness rotator cuff tears observed that the duration of symptoms was not related to weakness, limited range of motion, tear size, fatty atrophy, or validated patient-reported outcome measures. They concluded that using the duration of symptoms as a guide to recommend surgical repair of rotator cuff tears in order to reduce pain and improve function might not be the best approach. Masten et al. (2014)[64] tried to take some guidelines for the treatment of atraumatic rotator cuff tears from the existing data. They suggested if pain or stiffness is the main symptom, surgery may not be the ideal solution. In case of weakness as the primary problem, the surgeon should determine if a durable repair is achievable; if not, repair may not be in the best interest of the patient. And finally if instability is the issue, something more than a cuff repair such as reverse total shoulder arthroplasty may be needed.

In conclusion, patients are operated in different stages as there is not a consensus on the timing of surgery, and they have usually experienced a period of conservative treatments such as physical therapy or steroid injections. Surgeon's philosophy may affect the choice of aggressive approach. Post-surgical rehabilitation follows this philosophy and should be individualized based on patient's situation and surgeon's concerns. What we are presenting in this dissertation is actually a more dynamic and functional approach to the early rehabilitation after rotator cuff repair.

2.1.5 Surgical Options

Although the detailed information regarding the operation procedure is beyond the scope of this thesis, it is important to know how the integrity of repair can be affected by different surgical options. The surgery is often a combination of subacromial decompression and cuff repair which can be performed by open surgery or arthroscopy. It is believed that arthroscopic procedure may have advantages over standard open procedures including less trauma to the shoulder muscles, less pain, decreased morbidity and an earlier return of normal movement.[79] In mini-open technique for the cuff repair, after arthroscopic subacromial decompression, an open repair through a smaller approach without detachment of the deltoid will be followed. Clinical outcomes for arthroscopic repair and mini-open surgery are almost similar, however, higher rate of re-rupture for larger tears that repaired arthroscopically was reported.[10]
For partial tears, different operative treatments such as arthroscopic surgical debridement coupled with arthroscopic sub-acromial decompression,[80] arthroscopic conversion to a full-thickness tear with repair [81] or arthroscopic repair without conversion to a full-thickness tear[82] have been proposed. Biceps tenodesis in case of rotator cuff repair or biceps tenotomy in case of irreparable massive tear are routinely performed by some surgeons.[53]

A variety of methods and suture anchors have been developed to re-attach the torn tendon to bone. The arthroscopic repair can be performed by single- or double-row of suture anchors, using conventional methods, transosseous fixation or bridging sutures. All these methods aim to establish a fibrovascular interface between tendon and bone for healing and restoration of fibrocartilaginous tendon insertion. Therefore the goal of repair is to achieve a secure tendon to bone fixation while biological healing occurs. Tendon footprint contact area and contact pressure are critical factors that contribute to biological healing at the tendon–bone interface, and subsequently, long-term repair strength.[51] It was suggested that a larger area of contact between the tendon and bone may improve the biological healing process by increasing the size of the newly formed insertion site.[83] All the advancements in arthroscopic surgery and improvement of suture materials, anchors and technics have been directed to enhance the strength of repair. The ideal repair should provide high initial fixation strength, minimal gap formation, and high mechanical stability until completion of the tendon-to-bone healing process.[84] It has been shown that double-row repair gives better resistance to gap formation.[85]

Furthermore, smaller re-tear rate has been reported after double row technique than single row, although the clinical outcomes were similar.[86] According to a recent systematic review,[87] double raw repair provides superior structural healing to single-row repair. However, Apreleva et al. (2002)[83] suggested that trans-osseous simple suture fixation might provide greater potential for osseous incorporation and healing at the tendon-bone interface by increasing the repair-site area. Park et al. (2007)[88] have also suggested that the mean pressurized contact area between the tendon and tuberosity insertion footprint is superior using the suture-bridge technique to that of double-row technique. Anyway, optimal method of reconstruction is highly controversial and decision-making is therefore influenced by personal preferences, past experiences, surgical volumes and perceived results. But, it should be emphasized that the type of surgical approach can affect the post-op rehabilitation program. Optimizing the biomechanical properties of the repaired tendon allows for early postoperative rehabilitation while maintaining repair integrity. Therefore, along with improvement in surgical techniques and mechanical stability, the post-surgical treatments may progress from a highly conservative rehabilitation to more dynamic and functional rehabilitation. This issue will be discussed again in this dissertation.

2.1.6 Major Complications after Rotator Cuff Repair

2.1.6.1 Re-Tear

The prevalence of recurrent tear varies between 16% in young subjects with non-retraced tears[60] to 94% in massive cuff tears.[12] Bishop et al. (2006)[10] assessed postoperative cuff integrity by MRI and reported that 31% of repairs in the open surgery group and 47% in the arthroscopic group were not intact. Some authors reported a significant correlation between re-rupture and poorer outcomes. For example, Harryman et al. (1991)[89] in their evaluation of 105 tendon repairs noticed that the shoulders in which the repaired cuff was intact had better function during activities of daily living and a better range of active motion and strength. In their study, more than half of the repairs of a tear involving more than the supraspinatus tendon had a recurrent defect. However, improvement with respect to pain relief, range of motion and the ability to perform activities of daily living have been reported despite recurrent defects in the repaired tendon.[12] Despite all the debate over the relationship of repair integrity and pain or functional outcomes, the trend is toward a better outcome with intact repair.[90-92]

Several factors may be implicated in failure of the rotator cuff repair. Generally, chronic tears with muscle retraction and stiff musculo-tendinous unit have worse healing than the acute tears.[93] For this type of tears, large tensions are sometimes required to repair the tendon back to bone, and it was suggested that tension overload has a role in repair failure.[94,95] The suture tendon interface is the weakest region of the repair, and tissue failure typically occurs as a result of pull out through the tendon.[96] Inappropriate tension during rehabilitation may provide this situation. Anchors pulling out of bone, suture material breakage, surgical knot loosening and tendon pulling through sutures have been suggested as the potential causes for rotator cuff re-tearing.[97] Higher failure rate has been also reported for patients with lower bone mineral density and those who have higher fat infiltration in their infraspinatus.[98] Medical comorbidities may also impede rotator cuff healing. An animal study[99] has shown that diabetic rats had significantly lower fibrocartilage and organized collagen at the tendon-bone repair site and clinical studies have also reported worse result and higher rates of failure in diabetic patients.[100,101] Smoking has also been shown to increase the repair failure rate and worsen clinical results.[102] Therefore, repair integrity depends on different intrinsic and extrinsic factors; among them, post-op rehabilitation protocol is one of the most modifiable extrinsic factors.

2.1.6.2 Shoulder stiffness

Postoperative stiffness is one of the most frequent complications after rotator cuff repair. Warner and Greis. (1997) [103] in their studies on 500 cases of cuff repair, found 4% of painful loss of motion that was thought to be caused by postoperative adhesions. Huberty et al. (2009)[104] have reported 4.9% of stiffness in a series of 489 consecutive arthroscopic rotator cuff repairs and 3.1% of 576 arthroscopic rotator cuff repair cases had persistent postoperative stiffness in a multicenter study in France.[105] Higher incidence with a 32% significant persistent postoperative stiffness after mini-open rotator cuff repair has also been reported.[104] Severud et al. (2003)[106] compared the rate of stiffness between their arthroscopic and mini-open rotator cuff repairs and found a 14% incidence of postoperative adhesions and stiffness in the mini-open group and a 0% incidence in the arthroscopic group. Therefore, it seems that shoulder stiffness is more prevalent after mini-open or open procedures.

Shoulder stiffness can be a source of pain, functional limitation, and frustration for patients. Several risk factors for stiffness after arthroscopic rotator cuff repair have been identified including calcific tendinitis, adhesive capsulitis, single-tendon cuff repair, partial articular side tendon avulsion, concomitant labral repair, being under 50 years of age, and having workers'compensation insurance.[104] Typically, the patients in whom this problem develops have smaller rotator cuff tears, that is, they have a larger amount of tissue in the area that is available to participate in the inflammatory response.[107] Preoperative shoulder stiffness is also a risk factor for postoperative stiffness. Tauro et al. (2007)[108] in their retrospective review found that ROM did not improve postoperatively in patients with a preoperative total range of motion deficit of 70% or greater. Identification of risk factors for stiffness may be helpful to guide rehabilitation approaches.

The influence of early passive motion or immobilization on postsurgical stiffness is still of particular interest because, unlike other risk factors, it is directly under the clinician's control. A systematic review study[109] showed that immobilization protocols slightly increased resistant stiffness. This issue is the main theme of this dissertation that will be elaborated in the coming sections.

2.2 EARLY POST-OP REHABILITATION, WHAT ARE THE RATIONALES BEHIND

As detailed in the previous section, rotator cuff tendon repair is highly vulnerable to re-tear, and the capacity of the tendon to heal is limited. On the other hand, joint stiffness is a major post-op complication that causes patient's dissatisfaction. Postoperative rehabilitation program is a critical aspect in the treatment of rotator cuff injury that should provide recovery of joint range of motion, muscular strength and shoulder function, without preventing healing of the repaired tendon. There has been a general belief that a period of immobilization is needed for healing after operative treatment of rotator cuff tendon tears. Overloading the repair which may result to re-rupture is the main concern prohibiting the implementation of a functional postoperative treatment. However, while there are multiple studies on post-op treatment of Achilles tendon which confirmed that the functional treatments are safe and do not increase the risk of re-rupture, this issue has received minimal attention for the shoulder. Post-operative activity level is an important treatment component that still needs more research to be properly determined. In this section different studies concerning post-op immobilization strategy are reviewed.

2.2.1 Tendon Healing

After tendon injury or repair, three phases can be defined for tendon healing.[19,110,111] In the initial "inflammatory phase", inflammatory cells as well as platelet and erythrocytes will migrate to the wound site. These cells clean the site of necrotic materials and in the meantime, release vasoactive and chemotactic factors, which recruit tendon fibroblasts to begin collagen synthesis and deposition. The inflammatory phase characterizes by the development of a fibrin clot to stabilize the site, hemostasis, migration of neutrophils, macrophages, and erythrocytes, and subsequent neovascularization. This phase lasts almost one week and then the second stage which is "repairing phase" begins. In the proliferating or repairing phase, substantial cellular proliferation occurs and fibroblasts (tenocytes) synthesize collagen and extracellular matrix

(ECM) components throughout approximately one to four weeks following injury. However, the collagen produced is highly immature and disorganized. The final stage, “remodelling and maturation phase” begins approximately four weeks post injury and is characterized by decreased cellularity and decreased collagen and ECM synthesis. During this phase, ECM is remodelled to create a more organized structure through collagen turnover, realignment, and formation of collagen cross-links. Covalent bonding between collagen fibers causes higher stiffness and tensile strength of the repaired tissue.[19,110,111]

Rotator cuff has a short and intra-capsular tendon and its effective repair relies on tendon to bone integration. Rotator cuff tendon is different from long and sheeted tendons such as finger flexors in which the healing often depends on prevention of gapping and maintenance of tendon gliding. Rotator cuff injury mostly occurs at the tendon to bone insertion site where abundant fibroblasts produce a disorganized collagen tissue. The big difference in material properties in that region leads to high stress concentration. To overcome this challenge, tendon’s collagen fibers usually pass a transitional fibro-cartilaginous region into the bone. Some other strategies are also implemented, such as a shallow attachment angle at the insertion, shaping of tissue morphology of the transitional tissue, and inter-digitation of transitional tissue with bone. To improve tendon to bone healing, this zonal phenotype should be restored.[111]

It has been shown that mechanical loading has an important role in the development and homeostasis of tendon.[19] Mechanical loading induces gene expression and protein synthesis in fibroblasts. Disuse following immobilization has been shown to be associated with decreased levels of ECM protein expression, alterations in tenocyte morphology, and loss of normal ECM architecture.[19] These changes can result in impaired function and healing capacity. In addition, interruption of normal load transfer at the insertion site leads to a localized bone loss through increasing of osteoclast numbers in the repair site which may also impair healing.[112] Therefore, theoretically application of static or cyclic loading at the insertion site may be necessary for healing. However, while it is known that appropriate loading and tension play an important role in overall tendon function, the optimal time for incorporating loading regimens in post-op protocols is a matter of debate and yet the proper postsurgical rehabilitation strategy has not been completely defined. This thesis intends to show how a small amount of loading can be safely applied to rotator cuff tendon while shoulder joint is immobilized and no tensile pressure is imposed on the repaired site.

2.2.2 Animal Studies

Different animal studies have evaluated the effects of mobilization on tendon healing. Table 1 summarizes the existing animal investigations on non-rotator cuff tendons and rotator cuff tendon respectively. The table shows that the animal studies vary widely according to the tendon, evaluation methods for healing integrity and mobilization protocols.

Table 1: Animal studies concerning the effect of mobilization on tendon healing

A: non-rotator cuff tendons

Authors	Subject	Tendon	Protocol	Comments
Woo et al. [113] 1981	Canine	Flexor	Seven groups based on duration (3 to 12 w post repair) and mode of immobilization and partial mobilization	At 12 weeks, the repaired flexors from the motion group had regained over one-third of the ultimate tensile load with better gliding function.
Gelberman et al.[114] 1982	Canine	Flexor	1) Early passive motion 2) Delayed passive motion 3) Immobilization Groups were compared over a 12 w period	Early passive mobilization augments the physiologic processes that determine the strength and excursion of repaired flexor tendons.
Enwemeka et al.[115] 1992	Rabbits	Achilles Tendon	1) Immobilized post repair 2) Weight bearing and mobilization from day five post-repair	Functional loading augmented the tensile strength and energy absorption capacity of tenotomized tendons.
Murrell et al.[116] 1994	Rat	Achilles Tendon	1) Sham operation 2) Tendon transection without immobilization 3) Tendon rupture and application of Kirschner wires, 4) Tendon rupture and immobilization with Kirschner wires connected by two frames.	Group (4) had an additional, highly significant detrimental effect on the functional and mechanical recovery of Achilles tendon-calcaneal complexes.
Kamps et al. [117] 1994	Rabbits	Patellar tendon; central third removed	1) Control 2) Exercise on a treadmill for 12 w. 3) Immobilization for 12 w.	Early joint mobility produced large multi-axial stresses in original tendon leading to micro-damages. Less aggressive exercise or delay in joint mobility may help control tissue remodelling.
Yasuda et al.[20] 2000	34 Rabbits	Ruptured Achilles tendon without suture	1) Ankle immobilized 2) Both knee and ankle were immobilized	Knee immobilization retards the healing of a ruptured Achilles tendon

Palmes et al.[118] 2002	114 Mice	Achilles Tendon transected and sutured	1) Immobilization in equinus position 2) Mobilization through a limited ROM load to failure, tendon deflection and tendon stiffness up to 112th postoperative day	Complete regain of normal tendon stiffness in mobilization group *vs* half values in immobilized group. Increased inflammation in the early phase, but more mature tendon in the late phase.
Ertem et al. [119] 2002	20 Rabbits	Achilles tendon Repaired by Kessler technique	1) Cast immobilisation 2) Continuous early passive motion, 4 h/d Macroscopic and histologic examinations at week 6	The utilization of continuous controlled passive motion has beneficial effects on tendon healing and ankle range of motion, without leading to eventual ruptures.
Dagher et al.[120] 2009	60 Rats	ACL reconstruction with autograft	1) Immobilization with external fixation device 2) Normal cage activity postoperatively Immunohistochemistry in week 2 and 4	Early immobilization diminished macrophage accumulation that may allow improved tendon-bone integration
Bring et al. [121] 2010	32 Rats	Achilles tendon Ruptured 0.5 cm from the insertion	1) Free mobilization post-surgery 2) Immobilized with a plaster cast on their operated leg.	Prolonged immobilization hampers the healing process by compromising the up-regulation of repair gene expression in the healing tendon. A shorter period of immobilization, i.e. 1 week, would not impair the healing process significantly.
Bedi et al.[122] 2010	156 Rats	ACL reconstruction with flexor digitorum longus autograft	1) Immobilization 2) Controlled knee loading along the long axis of the graft • Immediately postoperatively • Post-op day 4: early delayed loading • Post-op day10: late delayed loading. Analysis: post-op day 14 or 28	Delayed application of cyclic axial load resulted in improved mechanical and biological parameters of tendon-to-bone healing compared with those associated with immediate loading or prolonged post-op immobilization of the knee.
Brophy et al [123] 2011	42 Rats	ACL reconstruction with flexor digitorum longus autograft	1) Immobilization group 2) Daily loading, for 14 or 28 days with cyclic displacement of the femur and tibia constrained to axial translation parallel to the graft.	Short-duration low-magnitude cyclic axial loading is not detrimental to the strength of the healing tendon-bone interface but is associated with greater inflammation and less bone formation in the tunnel in this rat model.

Hettrich et al. [124] 2014	192 Rats	Patellar tendon detachment and repair	1) Immobilization 2) Immediate post-op loading 3) Delayed onset loading (4-10 d delay) Axial tensile load , 50 cycles/ day	Immobilization resulted in a stronger tendon-bone complex, with less scar tissue and a more organized tendon-bone interface compared with all loading regimens in this study.

B: Rotator cuff tendon

Authors	Subject	Tendon	Protocol	Comments
Lewis et al. [125] 2000	16 Sheep	Infraspinatus tendons were reattached into a bone	1) Immobilized group with a softball taped under the foot for 6 weeks. 2) Non-immobilized group Evaluation after 26 weeks	No significant difference between the treatment groups for load-to-failure and stiffness.
Thomopoulos et al. [126] 2003	Rats	Supraspinatus detached and repaired	1) Immobilized group 2) Exercised group Biomechanical, structural, and compositional assays at 2, 8, or 16 weeks.	Viscoelastic properties and collagen organization was superior in the immobilization group. The ratio of type III to type I collagen, an indication of the level of scar in healing tissue, was highest in the exercise group.
Gimbel et al. [94] 2007	Rats	Supraspinatus detached and reattached to its insertion site	1) Shoulder immobilization 2) Cage activity or moderate exercise for durations of 4 or 16 weeks. Biomechanical testing and a quantitative polarized light microscopy method	Shoulder immobilization improved tendon to bone healing, by increasing the organization of the collagen and increasing the mechanical properties.
Sarver et al.[127] 2008	15 Rats	Supraspinatus detached and reattached to its insertion site	1) Not immobilized after injury and repair 2) Immobilized immediately after injury and repair in 90° of forward flexion and 90° of abduction in a plaster cast for 4 weeks. 3) Immobilized with no injury Passive shoulder mechanics measured before treatment and week 4 and 8 post-op	External rotation stiffness was significantly greater after 4 weeks of immobilization but not 8 weeks in immobilized group, i.e. increase in joint stiffness caused by immobilisation was transient.

Galatz et al. [128] 2009	Rats	Supraspinatus injury was created and repaired	Muscle paralysis after repair by Botulinum toxin A. Postoperatively: 1) Limb immobilized 2) Free ROM was allowed 3) Saline injected, casted rats as control Repairs were evaluated histologically, geometrically, and biomechanically.	Complete removal of load by paralysis was detrimental to rotator cuff healing, especially when combined with immobilization.
Peltz et al. [129] 2009	67 Rats	Supraspinatus injury was created and repaired	1) Continuous immobilization 2) Passive motion protocol 1, for two weeks 3) Passive motion protocol 2 for two weeks Remobilization for 4 weeks, passive shoulder mechanics was measured pre-op, week 2 and week6	Passive motion resulted in increased scar formation, decreased ROM and increased joint stiffness and did not have any effect on collagen organization or tendon mechanical properties measured six weeks after surgery.
Peltz et al.[130] 2010	22 Rats	Supraspinatus injury was created and repaired	Immobilisation postoperatively for 2 weeks; 1) Cage activity for 12 w 2) Exercise (gradual moderate treadmill running) for 12 w Tendon CSA and mechanical properties were measured.	After a short period of immobilization, increased activity is detrimental to both tendon mechanical properties and shoulder joint mechanics, presumably due to increased scar production.
Li et al. [131] 2010	16 Rabbits	Supraspinatus rupture and repair	Two weeks after operation: 1) CPM group 2) Non-CPM group (fed only) At 2, 4, 6, and 8 weeks, the tissue samples were verified for b-FGF expression.	CPM promoted b-FGF expression to enhance type III collagen synthesis at the tendon-bone interface in early stage of repair, contributing to tendon-bone healing after rotator cuff injury.
Hettrich et al.[132] 2010	132 Rats	Supraspinatus injury was created and repaired	1) Repair alone 2) Injections of botulinum toxin A into the muscle before repair. Histologic and biomechanical evaluation at 4, 8, and 24 weeks	Toxin–treated specimens had increased collagen fiber organization at 4 weeks but decreased mechanical properties at later time points.
Uezono et al.[133] 2014	72 Rats	Supraspinatus ruptured and re-constructed with	Shoulders immobilization for 2 weeks: (1) immobilization without PROM	Immediate passive motion was detrimental to remodeled tendon-to-bone healing and to the

	Acellular Dermal Matrix (ADM)Grafts	(2) immobilization with immediate PROM (the day after surgery) (3) immobilization with delayed PROM (1 week after surgery) Histological and biomechanical analysis at 2, 6, and 12 weeks postoperatively	tendon maturation of ADM grafts placed in the rotator cuff tendon defects. Delayed passive motion did no harm.

ROM = Range of Motion, CPM = Continuous Passive Motion, PROM= Passive Range of Motion, d= day, w = week

Considering the above data, it can be observed that animal studies have sometime contradictory findings. It may be because the response of tendon healing to mechanical load varies by anatomical location and tendon type. For example, for Achilles tendon, the effect of mobilization on tendon healing is highly supported by animal studies. Achilles tendon immobilisation exhibited decreased mechanical properties and healing process. Likewise, immobilization of canine flexor tendon promoted adhesion formation, therefore, passive motion could be beneficial for its healing. On the other hand, excessive motion in the setting of anterior cruciate ligament reconstruction, caused accumulation of macrophages, which might be detrimental to tendon graft healing. (see Table 1A for references).

Rotator cuff tendon has special characteristics that separate it from the others tendons. Firstly, rotator cuff tendon is not surrounded by a synovial sheet, so the adhesion formation is less likely the main problem for this tendon. Secondly, repairing flexor digitarum tendons or Achilles tendon rupture requires tendon-to-tendon healing, whereas repairing most rotator cuff tears requires tendon-to-bone healing. In this respect, reconstruction of anterior cruciate ligament may be more similar to rotator cuff repair. Most animal studies concerning healing of rotator cuff repair are in favor of a period of immobilization and the avoidance of large forces on the healing site; however, complete removal of load (e.g. muscle paralysis) has also been shown to be detrimental to the healing (see Table 1B). However, although these studies have provided invaluable information regarding the effect of mobilization on tendon-bone healing, they could not identify an optimal rehabilitation strategy.

The effect of immobilization on shoulder joint stiffness has been reported by Schollmeier et al. (1994)[134] on non-operated glenohumeral joint in dog model. Results showed reduced joint range of motion and capsular volume, increased intra-articular pressure and histological modifications such as those found in adhesive capsulitis in man. However, all of these modifications were reversible once the joint was exercised.[135] Following supraspinatus operation in rat model, Sarver et al [127] found a significant but transitory increase in stiffness during external rotation after 4 weeks of immobilization. On the other hand, some researchers have reported harmful effect of early but not delayed passive motion on glenohumeral range of motion due to scar formation favored by mechanical stresses.[129]

From all these animal studies, my interpretation is as follows:

For rotator cuff tendon repair, a period of immobilization is more warranted to reduce scar formation, and provide a safer environment for healing process, although the optimal duration of immobilization is not clear. During this period, in order to have better tendon healing, a balance must be reached between loads that are too low and non-effective in tendon homeostasis and too high leading to inflammatory flare-up, gap formation or microscopic damage. Complete load removal may deteriorate healing process. This deduction is followed during most of the studies presented in this dissertation, i.e. shoulder immobilization is preserved while minimal loadings are imposed on rotator cuff muscles.

2.2.3 **Clinical Studies**

Animal studies have provided scientific basis for many rehabilitation protocols. However, animal studies may not completely represent the changes in human bodies. Similar to animal studies, clinical investigations have also reported conflicting results in regard to application of load or immobilization following rotator cuff repair, and the debate still persists. Table 2 presents some published studies on early post-op rehabilitation strategies.

Table 2: Clinical studies on mobilization post rotator cuff repair

Author	Subjects	Protocol	Results
Raab et al. [136] 1996	26 patients after RCR	1) Routine physiotherapy 2) Physiotherapy + CPM Shoulder Scoring at 3 months follow-up: function, pain, strength, and ROM.	No difference in shoulder score between two groups. CPM has a beneficial effect on ROM for all patients, as well as on pain relief in female patients and patients ≥ 60 years of age
Lastayo et al.[137] 1998	31 patients with RCR: (5 small, 18 medium and 19 large tears)	Post operation: 1) CPM, for 4 weeks 2) Manual PROM, for 4 w	No significant differences between two groups with respect to the pain, ROM, or isometric strength. Manual passive ROM exercises were more cost-effective than continuous passive motion.
Hayes et al.[138] 2004	58 patients with RCR	1) Supervised physiotherapy treatment 2) Unsupervised home exercise regime. ROM, muscle force, functional outcome measured at 6, 12 and 24 w post-op	Outcomes for subjects allocated to individualised physiotherapy treatment after RCR are no better than for subjects allocated to a standardised home exercise regime.
Michael et al.[139] 2004	55 patients with RCR	1) CPM + physiotherapy 2) Physiotherapy alone time span to achieve 90˚ active abduction	CPM group reached the primary endpoint on average 12 days earlier than the control group with better result in controlling the pain and dysfunction.
Deutsch et al.[140] 2007	70 patients with RCR	1) Standard group: supine passive forward flexion in day 7 2) Decelerated group: the same at week 4 For both groups: Immobilization in an ultra-sling for 6 w pendulums exercise, post-op day #1, supine passive ER, post-op day #7 passive IR at 4 w.	No significant differences between groups for ROM, pain, and satisfaction scores. For both groups, re-tear rate: 35% of large to massive tears vs 4% of small to medium tears. No significant difference between the re-tear rates in two groups: (19% vs 9%), however, this difference may be clinically relevant.
Klineberg et al. [141] 2009	14 patients after RCR	1) Progressive Group: dynamic, specific muscle activation of RC post-op day 1 + PROM, sling for 4w 2) Traditional Group: traditional method, immobilization for 6 weeks, no load on RC	Larger reduction in pain during activity and at rest in progressive group compared with the traditional group in year 1 and 2 with no adverse effects.

Parsons et al.[142] 2010	43 patients with RCR	Full-time sling immobilization without formal therapy for 6 w post-repair At 6 to 8 w of follow-up, they were categorized to stiff and non-stiff Active ROM was assessed at 3 months, 6 months, and 1 year	In general, 23% were considered stiff in 6-8 w. At 1 year: No difference in ROM between two groups Repeat MRI suggested a trend toward a lower re-tear rate among the stiff patients.
Duzgun et al.[143] 2011	29 patients with RCR	1) Accelerated protocol: early active movement (week 3-4) in combination with preoperative rehabilitation. 2) Slow protocol: classical rehabilitation protocol	Accelerated protocol was associated with less pain during activity at weeks 5 and 16 and superior functional scores.
Arndt et al.[144] 2012	100 patients with supraspinatus repair	1) Immediate passive ROM 2) Restrict immobilization for 6 w Clinical evaluation + CT arthrogram	In immediate passive motion group: Better functional results Lower rate of adhesive capsulitis and complex regional pain syndrome. Non-significant but slightly better healing results with immobilization.
Cuff et al.[145] 2012	63 patients with supraspinatus repair (suture – bridge)	1) Early group: passive elevation and rotation post-op day 2 2) Delayed group: same protocol at week 6 Clinical monitoring: 12 w Healing was assessed by US	No significant differences in functional outcome, rotator cuff healing, or ROM between early and delayed groups. Slightly better healing rate in delayed group.
Kim et al.[146] 2012	105 patients with RCR	Abduction brace for 4 to 5 w 1) Early PROM: 3 to 4 times/ day during immobilization period. 2) No passive motion Functional score, pain and healing were assessed in 3, 6, 12 months	No statistical differences for pain, functional score or healing. Early passive motion exercise after arthroscopic cuff repair did not guarantee early gain of ROM or pain relief but also did not negatively affect cuff healing.
Lee et al.[147] 2012	64 patients with RCR Medium-large size tears	1) PROM exercises twice/ day from day 1 by physical therapist + home rehabilitation	Group 1 showed better ROM in 3 month but no significant difference between 2 groups after 1 y. (23.3%) in group 1 and (8.8%) in group 2 had re-tears, but the difference was not statistically significant.

		2) Only passive forward flexion up to 90° using CPM for 3 w, then increasing ROM as tolerated and other exercises. No active elevation until week 6. Tendon healing was assessed by MRI	
Keener et al. [148] 2014	124 patients With RCR with double raw technique for tear < 3cm	1) Rehabilitation program with early ROM 2) Immobilization with delayed ROM for 6 weeks. Clinical outcomes assessment in 3, 6, 12 and 24 months. Tendon integrity was assessed by US in 12 months.	Active elevation and external rotation were better in group 1 at 3 months. No significant differences in functional outcomes No difference in healing or re-tear rate
Koh et al.[149] 2014	88 patients with RCR (single-row) for postero-superior rotator cuff tear	1) Immobilization for 4 w 2) Immobilization for 8 w No passive or active ROM, including pendulum exercise Functional outcomes, re-tear rate by MRI	At 6 months post-op, 51% had stiffness, with no difference in two groups. Stiffness was higher in group 2 (38% compared with 18%) at 24 months post-op Re-tear rate 10% without any difference between groups.

RCR= Rotator Cuff Repair, CPM= Continuous Passive Motion, ROM= Range Of Motion, IR= Internal Rotation, ER= External Rotation, w = Week, d= day

The problem with the current clinical data is that they are not harmonized in study design, patient population, repair methods, statistical analysis and the definition of functional outcomes. Therefore, comparing the current studies is very difficult and hence, identifying the best rehabilitation strategy in the early phase after rotator cuff repair is challenging. Five systematic reviews tried to extract some conclusions from the persisting data. Huisstede et al. (2011)[150] assessed effectiveness of non-surgical and post-surgical interventions for symptomatic rotator cuff tears. For post-surgical strategy, they evaluated eight studies and reported that progressive physiotherapy and adding Continuous Passive Motion (CPM) to physiotherapy are not more effective than the traditional physiotherapy. They also could not find any evidence for the effectiveness of splinting in abduction versus resting the arm at the side. Three other meta-analyses, all have been published in 2014 focused on early post repair rehabilitation approaches and specifically the effect of early vs late passive movements on functional outcomes and cuff healing. Shen et al. (2014) [21] evaluated three RCT studies with 256 patients on total and noticed that there is not any evidence showing that immobilization after arthroscopic rotator cuff repair was superior to early-motion rehabilitation in terms of tendon healing. They identified that the subjects in the early-motion group regained their ROM more rapidly, with more external rotation at 6 months and a similar functional outcome compared with the immobilization group. Chang et al. (2014) [151] have also compared three RCT studies in respect of delayed vs early motion therapy. The delayed group required at least 4 weeks of shoulder immobilization, but shoulder pendulum exercises were permitted during this period. Early mobilization was defined as passive shoulder ROM exercises beginning within the first 2 weeks after cuff repair surgery. This meta-analysis could not identify any significant differences in functional outcomes and relative risks of recurrent tears between delayed and early motion in patients undergoing arthroscopic rotator cuff repairs. Riboh et al. (2014)[152] have also compared early passive motion with strict sling immobilization during the first 4 to 6 weeks after surgery. They selected five RCTs and their meta-analysis suggested that after primary arthroscopic rotator cuff repair of small to medium tears, early passive motion resulted in improved forward flexion and external rotation at 3 months. In this analysis, re-tear rates at a minimum of 1 year of follow-up were not clearly affected by type of rehabilitation. These reviews can be a guide for clinicians to implement passive ROM exercises as early as possible after rotator cuff repair. Recently (2015), a comprehensive meta-analysis compared the effect of early or delayed active range of motion on cuff healing.[153] Although there are not enough studies comparing the effect of early or delayed active motion on cuff integrity, this meta-analysis extracted the data from different studies on rotator cuff repair healing and compared the post-op protocols for 2251 repairs. In their investigation, the risk of a structural tendon defect was higher in the early versus delayed group for the tears ≤ 3 cm and repaired by trans-osseous plus single-row suture anchors. For tears > 3 cm, the risk of a structural tendon defect was higher in the early versus delayed group for suture bridge repairs and all repair methods combined. Finally, for tears > 5 cm, the risk of structural tendon defect was higher in the early versus delayed group for suture bridge repairs. They concluded that early active ROM may be harmful to the healing process for small and large tears regardless of repair method, and thus might not be advisable after rotator cuff repair. They suggested that delaying active ROM by at least 6 weeks after rotator cuff repair might be more appropriate for healing the tissue.

The above studies indicate that the repair site is better to be preserved from tensile forces and harmful loading by a period of immobilization. Passive ROM exercises may be applicable in this period without augmenting the risk of re-tear, but active ROM exercises are better to be avoided in the early period after rotator cuff repair. However, these studies could not determine the best method of immobilization as well as the best timing for passive ROM exercises.

2.2.4 Clinical Application & Challenges

Both animal and clinical studies on rotator cuff tendon repair are in favor of applying a period of immobilization post-repair for better healing result. However, the risk and benefits of early passive mobilization versus complete immobilization for tendon healing are not clearly identified in those studies. While animal studies are mostly in favour of more conservative approach after cuff repair, clinical studies are challenging the application of early passive ROM exercises. As mentioned earlier, basic science studies have shown that some loads are necessary for remodeling and maturation of healing site and provided theoretical support for early functional rehabilitation. However, timing and type of loading are still the matter of debate. It should be noticed that most recurrent tears develop within three to six months following surgery,[154,155] making functional rehabilitation more challenging during this time period. Could we consider some type of exercises or activities that impose safe range of load on cuff muscles and hence repaired tendon while respecting the beneficial effect of shoulder immobilization? This is exactly what I aim to challenge in this dissertation through my research studies.

It should be reminded that healing process is a multifactorial phenomenon and different internal and external factors influence on it. Therefore loading or mobilization should not be considered as an isolated factor, and hence, a unique regimen cannot be applied to everybody. Other influencing factors may affect the aggressiveness of therapy and mobilization protocols. Wilk et al. (2000)[156] listed eight factors that can significantly affect the decision making regarding a proper rehabilitation strategies (Table 3). Identifying these factors may help clinicians to determine how to proceed the treatment plan to help the tendon successfully heal to the tuberosity after repair. Major factors such as patient's age, size and chronicity of the tear, and muscle fatty degeneration and atrophy cannot be controlled, but they affect rehabilitation protocol. For example, patents with larger tears may have more muscle retraction that needs more tension and mobilisation of tendon to be attached to its bony insertion, so less aggressive physiotherapy may be more appropriate in those cases. It was suggested that fatty degeneration of the infraspinatus muscle can serve as an independent predictor of the postoperative integrity of the rotator cuff.[92] The surgeon's choice of repair technique can also affect postoperative rehabilitation regimens for the patients. For example, the patients with traditional open cuff repairs, may not be able to perform any active deltoid contraction for a couple of weeks, but in case of mini-open surgery, mild deltoid contraction in the earlier phases of rehabilitation may be feasible.

Table 3: Factors affecting rehabilitation protocol

Factor	**Details**
Type of repair	Open surgery, Mini-open or arthroscopy
Type of tear	Tear size, Number of tendons involved
Tissue quality	Good, Fair, poor
Location of tear	Superior, superior to posterior, superior to anterior
Onset of tissue failure	Acute vs gradual onset, Timing of repair
Patient variables	Age, dominant vs. non-dominant arm, pre-injury level, desired level of function (work/sport), comorbidities
Rehabilitation situation	Supervised vs. non-supervised
Surgeon's preference	Aggressive approach vs. conservative approach

Table derived from Wilk et al.[156] *with some modifications.*

To determine the optimal method of rehabilitation, the clinician should know how to balance the risk of structural failure with an increased risk of stiffness. Biomechanical and histological understandings of rotator cuff tendon to bone healing are necessary to safely manage post rotator cuff repair rehabilitation protocols. Most of the therapy protocols respect the basic science findings in tendon healing such as the histological timing of repair, the effect of loading on tendon healing, and controlling the tension on repaired tissue. It should be noticed that clinical study in the early phases after rotator cuff surgery is limited by ethical and technical considerations, therefore, relying on basic science findings is sometimes the only available option. However, clinicians may use all the persisting data in addition to experts' opinions or their personal experience to design a rehabilitation plan and individualize it according to the patient's situation. Figure 4 shows the common approaches for rotator cuff rehabilitation. In this figure two rehabilitation protocols are exemplified: protocol 1 is suggested by Wilk et al. (2000)[156] who are in favor of more aggressive rehabilitation and protocol 2 was offered by Miller et al. (2011) [155] with more conservative approach.

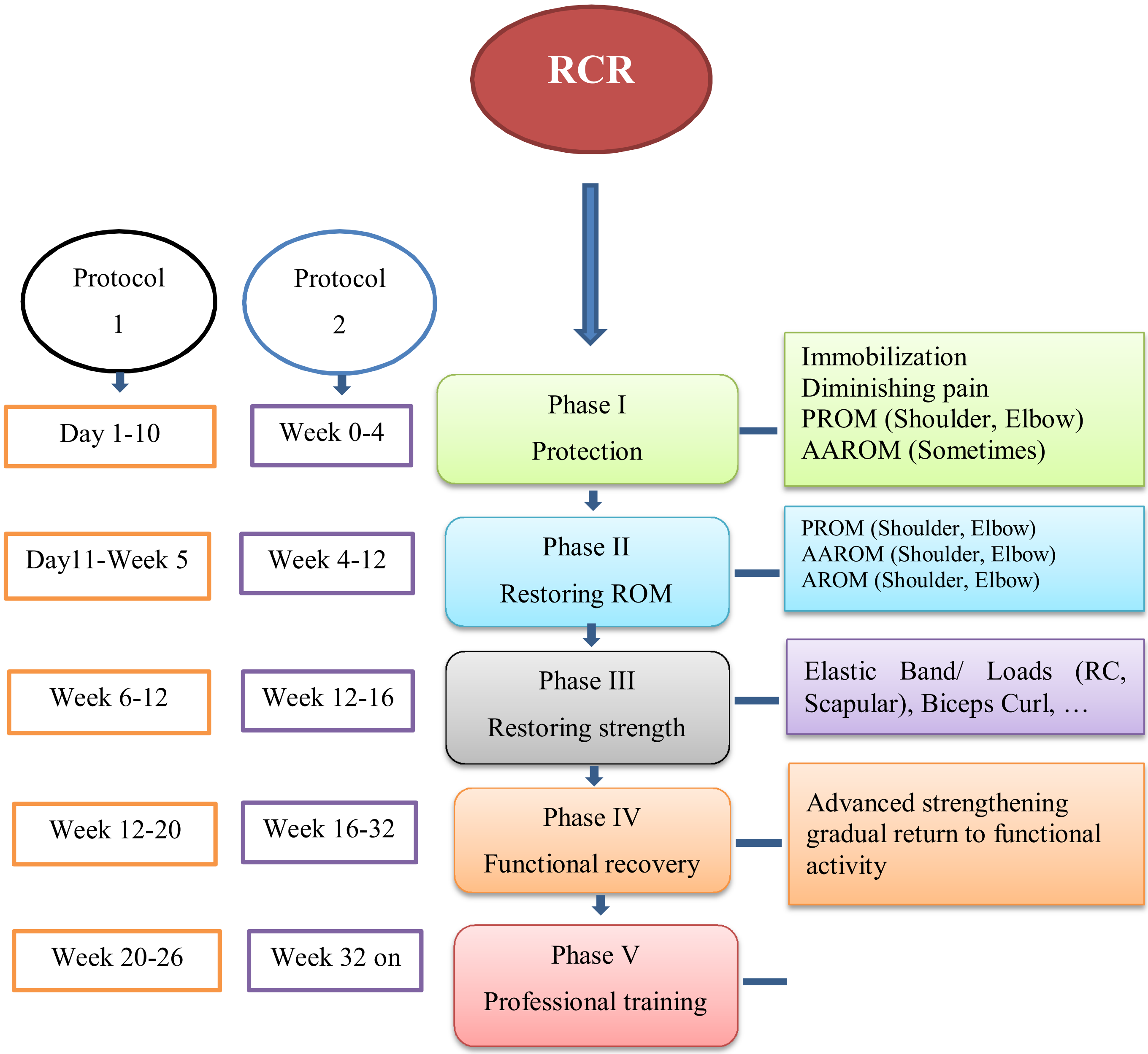

Figure 4: Schematic rehabilitation approaches, comparing two protocols with different timing

2.3 IMMOBILIZATION PROTOCOLS

2.3.1 Positioning: Sling *vs* Abduction Orthosis

Shoulder immobilization in early phases after surgery is widely prescribed by most clinicians. However the method of immobilization varies. Most clinicians prescribe a sling or an abduction orthosis (Fig 5). Choosing between sling and abduction orthosis may depend on the type of injury and the amount of abduction required to repair rotator cuff tendon with little or no tension. Watson et al. (1985)[157] in their study on 89 patients after rotator cuff repair reported that repair followed by splinting in abduction gave no better results than repair followed by resting the arm at the side. The poor results in their study were associated with larger cuff defects, more pre-operative steroid injections and pre-operative weakness of the deltoid muscle. Apart from this study, most other studies supported the idea of immobilization in an abduction position. It was reported that holding the arm in the resting position of adduction and neutral rotation could result in a hypovascularity of the supraspinatus [44] and eventually compromises the repair. Andres et al.[158] in an ovine model, demonstrated that increased abduction is associated with reduced tension and glenoid contact pressures and advised the use of abduction orthosis when the tension of repair is high. In a cadaveric study,[159] rotator cuff tear was created and repaired under a 3-kg tensile force with the arm in adduction. Strain on the repaired tendon was measured at 0°, 15°, 30°, and 45° of elevation in the sagittal, scapular, and coronal planes and from 60° of internal rotation to 60° of external rotation. The results showed that the strain level decreased significantly with the arm elevated more than 30° irrespective to the plane. However, stress level at above 30° of elevation in the scapular and coronal planes, increased with internal rotation and decreased with external rotation. They concluded that more than 30° of elevation in the coronal or scapular plane and rotation ranging from 0° to 60° of external rotation compose the safe range of motion after repair of the rotator cuff. Likewise, Howe et al. (2009)[160] in a cadaveric study monitored the tensions on sutures in 12 different positions after rotator cuff repair. In this model, 30° of either internal or external rotation of the arm in relation to the plane of the scapula created substantial imbalances in the tension between the most anterior and most posterior sutures of a supraspinatus repair, regardless of the position of abduction. They suggested that external rotation stretching should be avoided during the healing of supraspinatus repairs to prevent tension overload in the critical anterior sutures. In a similar study, Kulwicki et al. (2010)[161] reported that shoulder abduction from 45° to 60° had little effect on anchor tensions, however, 45° internal and external rotation significantly increased loads on the anterior and posterior anchors by at least 125%. Although these last two studies quantified the tension levels on suture anchors but none of them could identify how much tension might be detrimental for the repair. Reilly et al. (2004)[162] by using a combination of intraoperative measurements and cadaveric measurements quantified the relationship between passive tension of rotator cuff repairs and arm position and examined the effect of this tension on repair gap formation. In that study, an increase of 30° in abduction posture from neutral led to an average decrease in passive tension of 34 N, and an imposition of this tension in a cadaveric repair led to gap development. Finally, Jackson et al. (2013)[163] in our biomechanical lab, developed a generic musculoskeletal model of the shoulder to simulate postoperative immobilization of rotator cuff tears and verify the optimal postoperative immobilization postures that minimized the stresses in the repaired tendons. The results of this study recommended against using a standard sling, where the forearm is held against the abdomen, instead supporting the use of orthoses that elevate the humerus. Recently, Conti et al. (2015)[164] studied the clinical effects of two different braces after rotator cuff repair. In this study the upper limbs of 40 patients were immobilized either in a 15° of external rotation brace (ER Group), or an internal rotation sling (IR Group). They found that at short time after repair of isolated supraspinatus and also associated tear of infraspinatus, patients in ER group showed less pain and a better passive ROM. They did not find significant functional differences at 6 months of follow-up, however, patients immobilised in abduction and ER brace still showed a slight advantage in ROM.

It should be noticed that none of the previous studies addressed the positions of elbow and wrist in their immobilization protocols. Actually, most common slings or abduction orthoses, in addition to shoulder immobilization, routinely immobilize elbow and wrist joints (Figure 5). There is not any scientific evidence to support that elbow and wrist immobilization can reduce the level of loading and stress on the repaired tendon and hence help the healing. Respecting all the beneficial effects of immobilization in abduction position, we used abduction orthoses for our studies (produced by Médicus and Otto Buck), but small modifications have been performed on Médicus Orthosis in a way that the subjects could mobilize their elbows in horizontal plane and move their wrists in a full ROM. The orthoses that we used will be presented in chapter 3.

Figure 5 : Common shoulder orthoses

(Derived from google image, public advertisements)

2.3.2 Duration of Immobilization

The exact timeline for healing after rotator cuff repair in human body is unknown and so, there is not enough data showing the exact duration of immobilization for optimal tendon to bone healing. However, one study has found that 8 weeks of immobilization did not yield a higher rate of healing of medium-sized rotator cuff tears compared with 4 weeks of immobilization and increased the stiffness level.[149] Some authors tried to extract some conclusions from the current data and rationalize the immobilization duration according to the type of injury or repair. For example, Cohen et al. (2002)[165] suggested when tension of repair is minimal or none with arm at the side, a simple sling can be used for immobilization. They suggested immobilization for 1-3 weeks for small tears, 3-6 weeks for medium tears and 6-8 weeks for large and massive tears. They added when the minimal tension of repair is achieved by positioning the arm at 20-40° of abduction, then, using an abduction orthosis is more advisable. This type of orthosis is suggested to be used 6 weeks for small and medium sized tears and 8 weeks for large or massive tears. Wilk et al. (2000)[156] introduced three types of rehabilitation programs based on the patient's situation and tear size. Type I program is used for small tears in younger patients with good to excellent tissues. Type II is used for medium to large sized tears in active individuals with good tissues and type III is designed for large to massive size tears in patients with tenuous repair and fair to poor tissue quality. In type I program, 7-10 days immobilization by sling is recommended and achieving full ROM is planned for 4-6 weeks. In type II, 2-3 weeks immobilization by sling is suggested with full ROM in 8-10 weeks. For more conservative program in patients with large to massive tears, abduction pillow for 1-2 weeks, followed by sling immobilization for 2-3 weeks is recommended and full ROM is planned to be achieved in 10-14 weeks. Looking at rehabilitation literature, different protocols for post rotator cuff rehabilitation can be found. Most of these recommendations are not based on clinical studies and they are simply the experts' opinion. However, each study has its own justification based on the data provided by histological, physiological and biomechanical studies. In this respect, the biomechanical studies of the present manuscript can provide some basis for the extent of immobilization but cannot address the duration of immobilization.

2.3.3 Safe Exercises during Immobilization

Determining the safety level of a rehabilitation exercise is not an easy task. In clinical settings, an exercise can be considered safe if it does not increase the risk of re-tear which is the failure of surgery or post-op complications such as stiffness, inflammation or pain. Longitudinal clinical studies or randomised clinical trials can verify the safety of post- repair rehabilitation exercises, but unfortunately this type of studies is very few and therefore, most rehabilitation protocols are based on experts' views, case series or basic studies. As mentioned before, histological and biomechanical studies explained the nature of healing and the contributing factors in the healing process. Tension, force and torque are the common parameters being measured to determine the safety. High forced exercises and the activities that increase the tension on the repaired tendon are considered non-safe. But quantitative studies regarding the exact amount of force or torque that can deteriorate the repair healing is still lacking. EMG studies have provided a core conception for many rehabilitation programs. Higher EMG activity may indicate higher force generation within the muscle that may cause higher stress on tendon. This concept although has been usually used in EMG studies to scale the safety level. More explanation can be found in section 2.4 when EMG is deliberately discussed.

The exercises listed below are commonly prescribed for patients in the first phase of rehabilitation, corresponding to the first 4-6 weeks after rotator cuff surgery.

2.3.3.1 Shoulder Range of Motion Exercises

Table 2 presented the current data regarding the mobilization in the early phase after rotator cuff repair. Re-establishment of a safe range of motion after rotator cuff surgery has a paramount importance; however, the exact timing for starting ROM exercises is not clear. Two recent meta-analysis[151,152] suggested that early passive ROM (PROM) could decrease stiffness but in case of large tendon tears might result in improper tendon healing. Some authors[156] recommended PROM exercise in scapular plane with 45˚ of internal and external rotations immediately the day after surgery in patients with small to medium sized tears and good tissues, but for patients with large to massive tear, pendulum exercise and PROM are suggested to be conducted more gradually in the first week post-operation. Others[165] supported the application of PROM exercises in the first week after operation in the ranges that are dictated by safe shoulder motion in the operating room irrespective to the tear size. They recommended 140° of forward flexion, 40° of external rotation with the arm at the side and 60° of abduction without rotation. There is not any consensus in the timing of PROM exercises.

Most clinical data are discouraging early active ROM (AROM) in the first phase of rehabilitation concerning that it may increase the rate of re-tear.[153] AROM is usually postponed for 6-8 weeks post-operation according to the tear size and patient's progress. However, active assisted ROM in the later periods of the first phase of rehabilitation is usually prescribed. Few studies have shown that earlier AROM could improve the patient' functional scores.[141,143]

2.3.3.2 Elbow and wrist exercises

In most rehabilitation protocols, PROMs for elbow and wrist joints are performed during the first phase and gradually progressed to AROM. Isotonic exercises for elbow are advised near the end of the first phase as well as gripping exercises. Lifting of objects is usually discouraged. No study evaluated the effect of elbow, wrist or hand motions or resistance exercises on rotator cuff muscles. This topic is one of the main objective of my thesis which will be discussed in section 3.1 and 3.2.

2.3.3.3 Core body exercises

Some clinicians recognize the need to address the trunk and legs as the contributors of shoulder function. Kinetic chain shoulder rehabilitation integrates the exercises of legs and trunk with other shoulder exercises from the beginning of the rehabilitation program. It is believed that this type of rehabilitation would reinforce normal movement patterns and focus on the entire neuromuscular system.[166]

No resisting workout for rotator cuff muscles is allowed to be performed until 3-6 months after operation. However, if an exercise does not highly activate cuff muscles, or impose little tension on the repaired tendon, but highly activate the other shoulder muscles, it should be theoretically applicable in this period. My research studies will follow the same concept. I will suggest the exercises and positions that cause low activation within the rotator cuff muscles while some shoulder muscles are moderately active. We also present some type of exercises that involve a small range of arm active adduction and passive abduction. This issue will be discussed in section 3.2

2.4 EMG AND REHABILITATION STUDIES

2.4.1 An Introduction to EMG

(All the materials in this section and its sub-sections have been derived from the references 167-169). [167-169]

Electromyography (EMG) is an experimental technique for studying the muscle function and dysfunction. The basis for EMG is development, recording and analysis of myoelectric signals which are formed by physiological variations in the state of muscle fiber membranes. EMG can be used in both clinical and basic science studies, however, there are many practical and technical considerations in the application and interpretation of EMG signals. As many papers that analyse muscle activity during shoulder exercises (like my studies) involve the use of EMG, it is important to understand what EMG is, how the signals are interpreted and what information EMG can and cannot provide.

2.4.1.1 Molecular and chemical Basis

The Neural and skeletal muscle membranes are the main seat for bioelectric changes that result in EMG signals. Cell membrane potential is an electrical potential difference across the membrane which is dependent to the ionic concentration on each side of the membrane. The transmembrane potential is zero when concentrations of negatively and positively-charged ions are equal on each side. This equilibrium is maintained by ion channels through them the ions can be transferred across the membrane, down their electrochemical transmembrane gradients. Generally, channels will allow the passage of positively or negatively charged ions, but not both. When the K+ channels open, K+ ions, which have higher concentrations in the cytoplasm, diffuse down their concentration gradient through the membrane. However, negatively-charged counterbalancing anions, such as proteins, other organic anions and chloride, cannot cross through the K+ selective ion channels and this imbalance creates a negative electrical potential in cytoplasmic side. The resting potential of muscle fiber membrane is approximately -70 to -90 mV. This negative potential drives K+ ions back across the membrane into the cytoplasm. The membrane contains voltage-gated Na+ channels too that permit the rapid passage of Na+ ions. At rest, the membrane is more permeable to K+ than to Na+.

Excitation transferred by a motor neuron causes Na+ channels open more rapidly than do K+ channels and Na+ ions flow in (**depolarization**). This influx of Na+ further depolarizes the membrane and continues until a critical threshold potential is reached, when Na+ influx exceeds K+ efflux. In this situation, there is an explosive positive cycle of opening of Na+ channels, results in an **action potential** (AP) often called a 'spike'. At this peak positive level, membrane permeability to Na+ may be up to 50 times than to K+. If a certain threshold level is exceeded within the Na+ influx, the depolarization of the membrane causes an action potential to quickly change from –70 mV up to +30 mV which is immediately restored by backward exchange of ions within the active ion pump mechanism; the **repolarization.** In repolarization, the membrane potential returns to negative values due to inactivation of voltage-gated Na+ channels and it may become, briefly, more negative than the resting potential of the axon membrane (**hyperpolarizing**) because K+ channels dominate electrical determinants of the membrane potential. As more K+ channels become inactivated, membrane potential returns to the resting value. Figure 6 illustrates the above explanations.

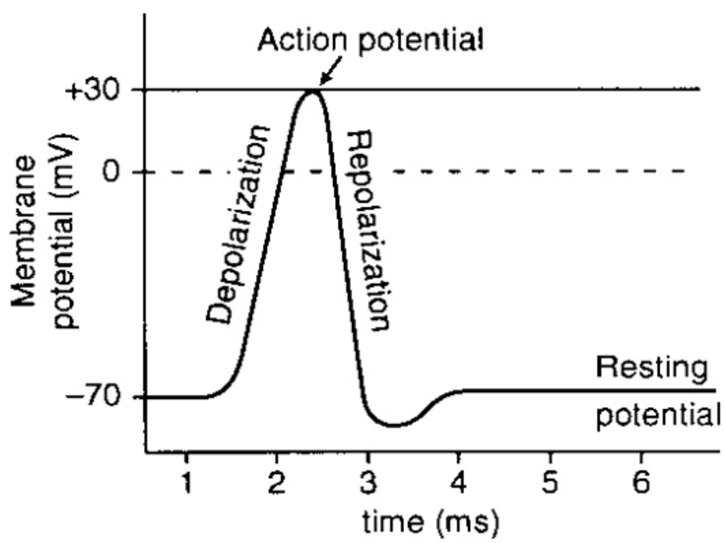

Figure 6: EMG Signal Cycle

'Figure derived from google image, labeled for re-use with modification'

The neuromuscular junction is the synapse where electrical information is chemically transmitted from nerve to skeletal muscle. The nerve is the motoneuron, which has its cell body in the spinal cord, and whose axon terminates at the **motor end-plate** of the muscle (Fig 7). The smallest subunit in a muscle that can be controlled is a motor unit because it is innervated separately by a motor axon.

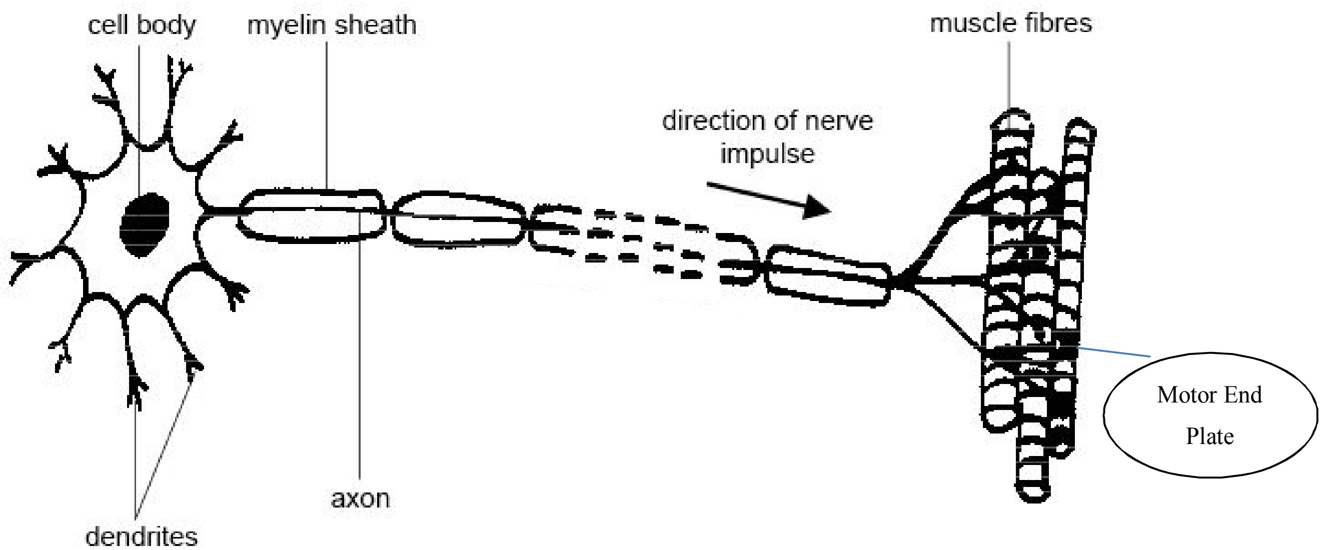

Figure 7: Motor Unit

'Figure derived from google image, labeled for re-use with modification'

The electrical information from nerve is transduced to a chemical signal in the form of a neurotransmitter, (acetylcholine) which is transduced back to an action potential (AP) in the muscle. Starting from the motor end plates, the action potential spreads along the muscle fiber in both directions and inside the muscle fiber through a tubular system. This excitation leads to the release of calcium ions, which trigger the fusion of vesicles full of acetylcholine with the nerve terminal membrane, and this results in the opening of the receptor channel to Na+. The resultant stimulation of the muscle end plate is called an **end plate potential** that in turn opens voltage-gated Na+ channels to cause the AP to fire off and finally produces a shortening of the contractile elements of the muscle cell.

In a healthy muscle, any form of muscle contraction is accompanied by the described mechanisms. The EMG signal is based upon APs at the muscle fiber membrane resulting from depolarization and repolarization processes. The extent of this depolarization zone is approximately 1-3 mm^2 and this zone travels along the muscle fiber at a velocity of 2-6 m/s and passes the electrode side. A motor unit may contain widely different numbers of muscle fibers, ranging from 10 to 15 in the extra-ocular muscles to over 500 in large limb muscles such as the gastrocnemius. Each muscle has a finite number of motor units, each of which is controlled by a separate nerve ending. In each fascicle of muscle fibers, usually several motor units are represented in a scattered fashion. A single motor unit may occupy a relatively large portion of a cross section of a muscle, called the motor unit territory. In human limb muscles, the average motor unit territory has an irregular round shape with a diameter of about 10 mm. Excitation of each unit is an all or nothing event, it means that all the muscle fibers of a motor unit are discharged nearly synchronously upon the arrival of a nerve impulse along the axon and through its terminal branches to the motor end plates. The electrical signal generated in the muscle fibers as the result of recruitment of a motor unit is a **motor unit action potential (MUAP)**. Depending on the type of electrodes used, the recorded MUAP can be derived from APs of a small number of muscle fibers (1–3), a moderate number of muscle fibers (15–20), or a great majority of muscle fibers (several hundreds). Electrodes placed on the surface of a muscle or inside the muscle tissue will record the algebraic sum of all MUAP's being transmitted along the muscle fibers at that point in time.

2.4.1.2 Detecting EMG signals: surface *vs* intramuscular electrodes

Based on the size and site of the muscle under investigation, EMG signals can be detected by intramuscular or surface electrodes. The detection electrode is typically bipolar and the signal is amplified differentially. Surface electrodes which consist of disks of silver/silver chloride metal, generally detect the activity of superficial muscles, e.g. deltoid or pectoralis major. To determine the activity from muscles located deep in the body, assessment of fine movements and for recording motor unit activity, the indwelling electrodes are more preferable.[170] Therefore, the activities of deep rotator cuff muscles are better to be detected by indwelling electrodes.

In kinesiological EMG, the most common type of intramuscular electrode in use is the fine wire electrode which consists of a pair of extremely fine nylon-coated wires (diameter of 50μm or less) placed in situ by means of a hypodermic needle. The needle is withdrawn and a small hook or barb at the end of the wires keeps them in the muscle (Figure 8). Such electrodes may be driven easily into the belly of a deep muscle without anaesthesia causing no more pain than that resulting from the needle puncture itself. Fine wire recording have an increased sensitivity to power hum because of the unshielded wire endings. Therefore, it is important to check and establish the electrical environment during intramuscular EMG studies.

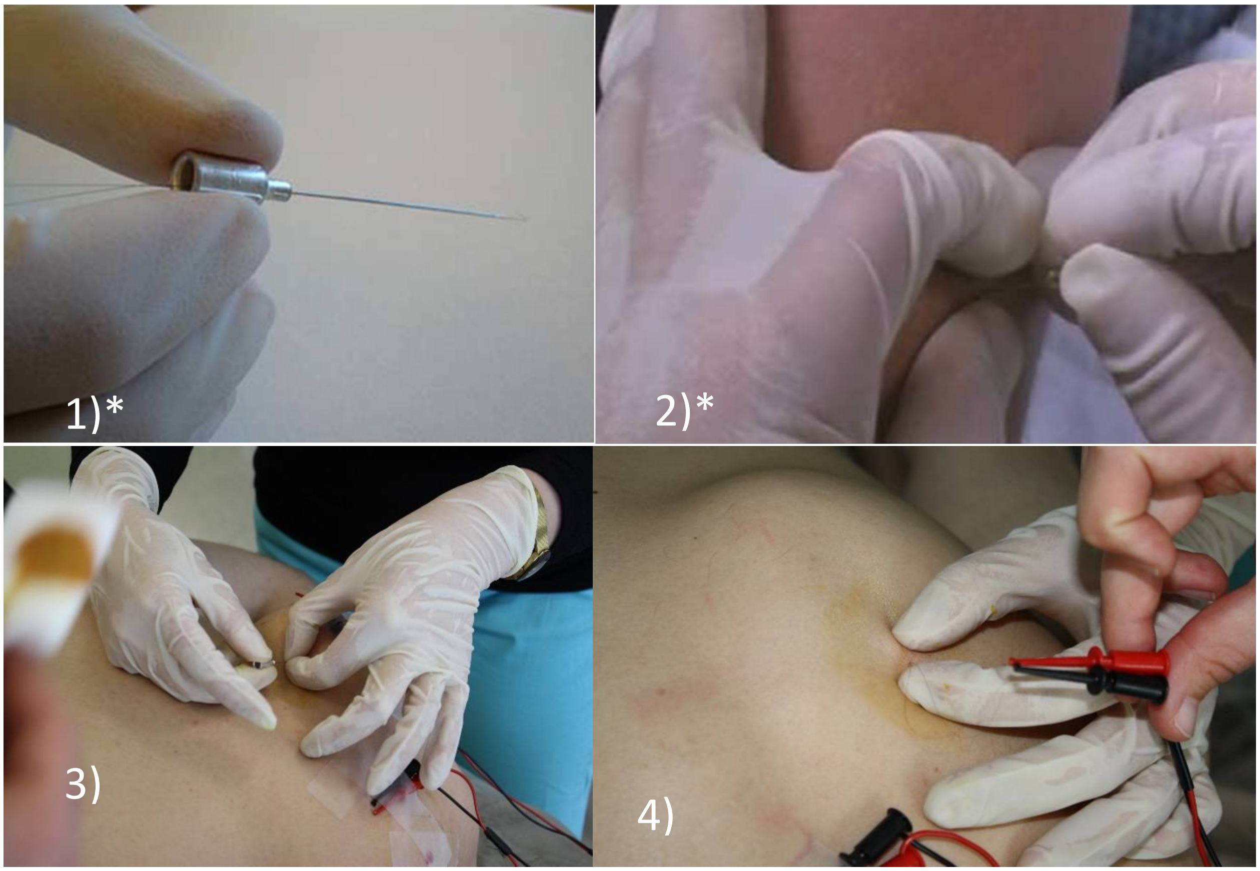

Figure 8: Insertion technique for fine wire electrodes

*1) Needle with wires, 2) insertion of the needle into the muscle, 3) needle is withdrawn, 4) fine wires are hooked in the muscle, * derived from Rudroff (2008)*[177]

Table 4 presents the advantages and disadvantages of intramuscular EMGs. Fine wire electrodes have a small detection area and they record from a more localized area of the muscle, thus this technique gains a better degree of specificity. The minimal diameter of recording wire is particularly suitable for dynamic EMG analysis. However, they may be criticized on the basis that the small sample area is not representative of the whole muscle,[171] especially if motor units are not homogeneously distributed throughout the muscle body. In addition, a disadvantage of the fine wire technique is that its reliability coefficients are lower than for surface electrodes.[172] Although fine wire electrodes can be manipulated while monitoring EMG activity and are suitable for clinical investigations, accurate placement of fine wire electrodes is more difficult than with surface EMG. They must hook into the desired muscle layer and cannot be repositioned once inserted. Finally, the invasive insertion technique, makes intramuscular EMG more challenging from both technical and ethical standpoints. However, fine wire electrodes are superior for prolonged and non-clinical investigations of muscle function because they are hooked in the muscle fibers and therefore move with the fibers ensuring that the recording area is the same.

Intramuscular EMG is the preferred method for detecting the activity of rotator cuff muscles in shoulder studies. In all studies presented in this dissertation, we used fine wire electrodes to evaluate the activity of rotator cuff muscles. Appendix 3 deliberately explains the methods of needle insertion in each of the four rotator cuff muscles that we used in our biomechanics lab.

Table 4: Advantages and disadvantages of fine wire electrodes

Advantages	**Disadvantages**
More sensitive	Invasive technique
Better specificity	Repositioning is impossible
Access to deep muscles	Small detection area
Lower cross-talk	Increased sensitivity to power hum and motion

Surface EMG is non-invasive and detects activation from a wider volume of the muscle. However, EMG recordings from thin and deep muscles are difficult to obtain due to **crosstalk** from adjacent muscle layers. Crosstalk is the signal detected over a muscle but generated by another muscle close to the first one. This phenomenon is present exclusively in surface recordings, when the distance of the detection points from the sources may be similar for the different sources. Crosstalk is one of the most important sources of error in interpreting surface EMG signals. This is because crosstalk signals can be confounded with the signals generated by the muscle, which may be considered active when indeed it is not. Crosstalk is a major problem when surface electrodes are used in the shoulder region. However, when large muscle groups such as the trapezius, pectorals major or deltoid muscles are investigated, surface electrodes give a more global evaluation of muscle activity than do fine wire electrodes, which measure a rather small selection of muscle fibers. Winter (1994) [173] estimated that 90% of a surface EMG signal has its origin within a 12-mm distance from an electrode pair. As crosstalk is usually caused by distant motor units, it primarily contributes low frequency components to the EMG. By processing the EMG through a differentiator, the higher frequency (closer) MUAP's are emphasized while the lower-frequency (further) MUAP's are attenuated.[167,174]

In our studies we used surface electrodes for three parts of deltoid, three parts of trapezius, latissimus dorsi, pectoralis major, biceps, triceps and serratus anterior. Some researchers prefer fine wire electrodes rather than surface electrodes to detect the activity of serratus anterior. There is an study[175] indicating that intramuscular electrodes could be representative of activity in serratus anterior as surface electrodes, however, intramuscular electrodes are better for investigation of lower serratus anterior activity pattern during functional activities that cause considerable displacement of surface electrodes. In that study, the researchers could not find any evidence indicating that crosstalk is contaminating the signals recorded from the surface electrodes. We preferred to use superficial EMG to detect the activity of serratus anterior, because our main interest was rotator cuff muscles and we intended to minimize the number of invasive procedures especially for our patient population. In addition, most of our experiments have been performed while the shoulder was immobilized and hence, the possibility of surface electrode displacement was minimal (Figure 9).

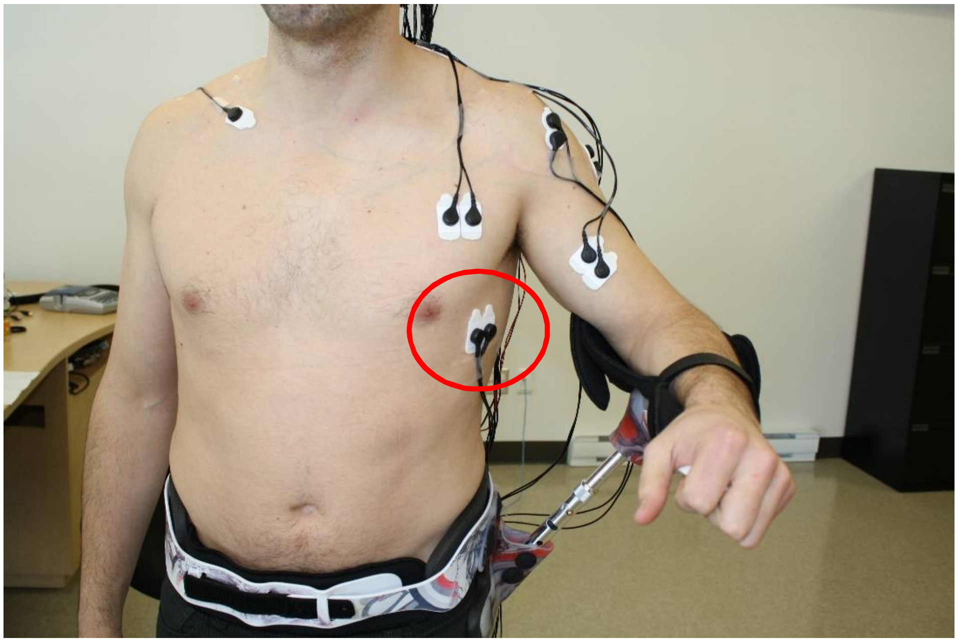

Figure 9: the location of surface electrodes for serratus anterior in respect to the arm position

2.4.1.3 EMG signals: how they behave, how we treat them

The healthy relaxed muscle shows no significant EMG activity due to lack of depolarization and action potentials. With proper skin preparation, the averaged baseline noise should not be higher than 3-5 microvolts. By muscle activation, EMG signals appear. The EMG signal is a time dependent signal whose amplitude varies in a random nature above and below the zero value. Raw surface EMG amplitude can range between ±5 mV while the indwelling electrodes can have larger amplitude up to 10 mV as recorded during maximal voluntary contraction (MVC) testing. Typically the frequency contents of EMG range between 5 and 500 Hz, showing most frequency power between ~ 20 and 150 Hz. The shape of recorded AP of a muscle fiber is typically triphasic, and the signal amplitude decreases exponentially as the distance between the electrode and the muscle fibers from which the recording is made increases. Thus the contribution of any individual muscle fiber to the MUAP amplitude crucially depends on its distance from the active electrode surface. A change of the shape of the MUAP changes the frequency content of the EMG signal. The amplitude of the action potentials is dependent on the diameter of the muscle fiber, muscle length and muscle fatigue.[170,174] In addition, the number of muscle units (MUs) and their density can affect the signal complexity. Smaller muscles, such as the first dorsal interosseous, compared to larger muscles, such as the biceps brachii, have fewer MUs and use large amounts of rate coding. Therefore, for comparable maximal contractions, smaller muscles will on average generate more complex signals than signals detected in larger muscles.[176]

Raw EMG by itself contains valuable qualitative information about “off-on” and “more-less” characteristics of muscle activity. But for quantitative amplitude analysis, specific signal processing steps should be applied to increase the reliability and validity of findings. First of all, to avoid anti-aliasing effects within sampling, a special band-pass filter for the amplifier should be set. A filter is a system that allow certain frequency to pass to its output and reject all other signals. Low end cut-off removes electrical noise associated with wire moving and biological artifacts. High end cut-off eliminates tissue noise at the electrode site. Recommended range of the EMG amplifiers is 10-1000 Hz for surface electrodes and 20-2000 Hz for indwelling electrodes. Considering the special setting of our EMG machine (Model15A54, Grass Technology), we used bandwidth 10-1000 Hz for surface electrodes and 10-3000 Hz for indwelling electrodes. In certain situation, application of additional digital filtering is suitable. “Notch filters” cancel out certain frequency contents of the signal, e.g. 50 or 60 Hz artifact cycles of electrical noise. The signal loss is acceptable for amplitude oriented analysis like the studies in this dissertation, but for EMG investigations using frequency analysis parameters, notch filtering should not be used because signal energy loss can occur.

The raw EMG spikes are of random shape, which means one raw recording burst cannot be precisely reproduced in exact shape. This is due to the fact that the actual set of recruited motor units constantly changes within the matrix/diameter of available motor units. If occasionally two or more motor units fire at the same time and they are located near the electrodes, they produce a strong superposition spike. To address this problem, the non-reproducible part of the signal should be minimized while the mean trend of signal should be outlined. This processing of EMG signals contains three parts:

1) Filtering again! In most EMG studies, Butterworth filtering is commonly used. The Butterworth filter is an optimal filter with maximally flat response in the passband. This passband frequency must be decided by the analyzer, once it can depend on the intentions of the study. Usually, this frequency is fixed between 20 and 450 Hz, because normally 80% of the muscular energy is concentrated in this range. We set the frequency at 20-400 Hz for our EMG studies.

2) Rectification: EMG contains a varying negative, positive alternative current signal. By rectification, all negative values converted to positive values and by adding the total values, turn all the signal values integrative, (absolute value).

3) **Smoothing:** Like filtering the aim of signal smoothing is to taking out the extremes. Smoothing creates a linear envelope in the signal, leaving only a center part of the signal. The mainly difference between the smoothing and the filtration, is that filtration takes in account the muscle activation range, and in smoothing the signal obtained itself. Two algorithms are generally used: 1) Moving average: in this method, the user defines a time window, then, a certain amount of data are averaged using the gliding window technique. It relates to information about the area under the selected signal epoch. 2) Root Mean Square (RMS): reflects the mean power of signal based on the square root calculation. RMS is the preferred method for smoothing.[168] Both algorithms are defined for a time window which typically changes between 20 ms for fast movement to 500 ms for slow or static activities. For our studies, we chose RMS algorithm with a time window of 100 ms. By applying a smoothing algorithm or selecting a proper amplitude parameter the non- reproducible contents of the signal is eliminated or at least minimized.[167,170,177] How these smoothed signals should be interpreted? The next section will answer this question.

2.4.1.4 Normalization: how to interpret the EMG signals

A generalized representation of the EMG signal must contain a formulation which allows a comparison of the signal between different muscles and individuals. Therefore, for accurate documentation of the muscle activities between muscles or between conditions, some type of normalization is required. The goal of any normalization technique is to identify a relative reference point that is consistent across muscles, across exertions, as well as across subjects to ensure that EMG signals are useful in identifying muscle dysfunction and evaluate treatment outcome. Here I introduce different methods of normalization for shoulder muscles and the ones that we used for normalizing our data.

1- Maximum Voluntary Isometric Contraction

Maximum Voluntary Isometric Contraction (MVIC) is the most popular method of EMG normalization which is commonly used for EMG studies of shoulder musculature. In this method, the maximal contractions are performed against static resistances. Different studies tried to identify the optimal manual muscle testing positions that elicit maximal neural activation for shoulder muscles.[178] [179] [180] Considering the popularity of this method, we used MVIC for normalizing the EMG data of our healthy subjects. However, we acknowledge that this method has its own specific limitations: First, the reproducibility of MVIC for different muscles is under question.[181] Normal subjects may have problems producing a true MVIC contraction level, for not being used to such efforts. Without training, the MVIC could be as much as 20-30% less than that obtained after appropriate training.[182] The reproducibility of this reference point also depends upon the level of motivation solicited during the exertion. In other word, MVIC normalization method relies upon a "true" maximum exertion, while MVIC may vary depending upon the training and motivation of the individual. This MVIC variability may influence the interpretation of the EMG signal and may introduce some level of experimental error. To overcome this problem, Baratta et al. (1998)[183] introduced a method that required the subject to perform a maximum exertion, followed by a series of successive exertions that increased by 10%. Once the subject was no longer able to achieve a targeted exertion, the previous successful level was identified as the MVIC. However, this method is very time consuming and has limited utility. In our lab, we trained our subjects how to perform each MVIC test by showing them the exact positioning by PowerPoint slides and one of the researchers corrected their positions in the try-outs. The verbal encouraging method has been also applied.

Second, logically patients cannot or should not perform MVICs with injured structures. In addition, EMG activity level can change with soreness or pain. It has been shown that sore muscles following repetitive eccentric exercise would have lower strength, [184,185] and therefore cannot create maximal contractions. Furthermore, muscle pain, even in the absence of obvious pathology (such as the cases with fibromyalgia) can reduce MVIC level [186,187] and EMG activity [188]. It is not clear if the pain of indwelling electrodes can affect the MVIC values or not. Anyway, we know that the patient with pain, soreness and discomfort may show lower level of MVIC and it may affect the normalization process. That is why we did not use this method in our third study on symptomatic cuff patients.

Third, MVIC normalization is also criticized for EMG studies of an unrestricted dynamic task, such as walking or cycling. In these studies, the data may be normalized with respect to an EMG value taken during a single maximum voluntary contraction performed at one reference joint angle, while at different joint angles, there are changes in the length/tension relationship of the muscle which would cause changes in the maximum EMG value.[189] As most of our studies on shoulder musculature was performed when the shoulder was immobilized, so the latter critic is not relevant to our cases.

2- **Sub-maximal voluntary isometric contraction** (sub-MVIC)

In this method, the peak EMG from a submaximal isometric voluntary contraction is the reference point. According to Yang and Winter (1983) [181], this method has superior reliability and can provide a more stable reference value. However, determining the actual relative level of effort for a given muscle in a multiple muscle system is problematic particularly for arbitrarily selected sub-maximum exertions. Dankaerts et al.(2004)[190] compared MVIC and sub-MVIC methods for interpreting the EMG of trunk musculature. They found excellent within-day reliability for both MVIC and sub-MVIC methods in healthy controls and patients with low back pain. However, the reliability of sub-MVIC in between-days was higher than MVIC method in both groups. As our studies did not include between-day comparisons, we preferred to use the maximal values for EMG normalization in two of our research studies.

3- **Maximal or Sub-Maximal Dynamic Voluntary Contraction**

In this method, the peak EMG from a maximal non-isometric voluntary contraction with the same muscle action, and joint angle or muscle length is the reference point. In angle and angular velocity specific maximal isokinetic voluntary contractions, the peak EMG from a maximal isokinetic voluntary contraction with the same muscle action, joint angle or muscle length is used for normalization. Burden and Bartlett (1999)[191] compared four different methods of normalising EMG signals from the biceps brachii, including isotonic contractions of the elbow flexors with an external force of 50 N, 100 N, 150 N and 200 N, followed by a single isometric maximal voluntary contraction (MVC) and ten isokinetic MVCs at 0.35 rad/ s intervals. They suggested that only the isometric and isokinetic MVC methods should be used to normalise the amplitude of EMGs from the biceps brachii.

4- **Mean or Peak amplitude**

These include normalisation using either the peak or mean signal measured during a task. The mean or peak EMG from the task under investigation usually obtained from an ensemble average rather than a single trial. Although these methods do not give the information on the absolute degree of activation which MVC normalisation provides, they do provide information about the pattern of activity. Yang and Winter (1984)[192] were the first authors to discover that both the Mean Task and Peak Task methods reduced inter-individual variability, in relation to the un-normalized EMGs during walking. Morris et al. (1998)[193] conducted a study to assess three normalisation methods (MVC, peak and mean signal) for shoulder muscles in healthy subjects. EMG data from shoulder musculature including the rotator cuff was collected during five types of exercises on an isokinetic muscle dynamometer. Interestingly the pre- and post-exercise MVC voltages showed a marked variation which the authors contributed it to the migration of the electrodes during the experiments or the different recruitment pattern during pre- and post-protocol MVC. They criticized using MVC as a normalisation method for shoulder dual fine wire electromyography and suggested that normalisation using the mean or peak value of a movement cycle would be more appropriate because they created more similar pattern of activity for each of the intramuscular electrodes. We used the mean values for normalizing the EMG data driven from symptomatic subjects with rotator cuff tears. This method could help us to evaluate the EMG pattern in certain movements, without imposing harmful contraction to create MVIC.

For the dynamic events, such as gait, the peak or mean EMG can be also another alternative to MVC for data normalization.[192] However, Knutson et al. (1994)[194] studied the reliability of different normalization approaches by evaluating the gastrocnemius EMG resulted from 20 normal persons and 20 individuals with anterior cruciate deficiency during balance board activity. The data was normalized to MVIC, peak dynamic EMG, and mean dynamic EMG. They observed that the variance ratio and intra-class correlation coefficient were best with EMG from the MVIC which suggested better reproducibility of this method.

5- EMG-Moment reference point

Marras and Davis (2001)[195] constructed a database from studies performed in their biodynamics laboratory. This database included individual anthropometric measurements of 120 subjects as well as the maximum exerted trunk moments generated during MVC exertions for normalization purposes. They developed regression equations to predict the maximum contraction moments from various anthropometric measurements. In addition, they asked 20 subjects to perform sub-maximal and maximal exertions to determine the necessary characteristic exertions needed for normalization purposes. They suggested that an EMG-moment reference point can be obtained via a set of sub-maximal exertions in combination with a predicted maximal exertion based upon anthropometric measurements. This method is based on the observation of a highly linear relationship between EMG muscle activity and trunk moment for most of the trunk muscles. Such a relationship for shoulder muscle has not yet been established.

6- Base-line activity

In this method, which is not very popular, the activity levels for each repetition is reported as a percentage of the activity observed during quiet stance at base line. This method is more appropriate for patients who are unable to do maximal or submaximal exertion. Murphy et al. (2012)[196] normalized the EMG data of shoulder musculature driven from patients after sub-acromial decompression surgery to compare different passive rehabilitation exercises. They aimed to identify and compare exercises that elicited greater activity than found at rest.

7- EMG expressed as "Muscle Activation Ratio"

This is another method of reporting EMG data used by de Witte et al.(2012)[197] to normalize and report the EMG data in patients with rotator cuff tears. In this study, the EMG of abductor and adductor muscles were expressed using the "Activation Ratio (AR)" ($-1 \leqslant AR \leqslant 1$), where lower values express more co-activation. In order to calculate the Activation Ratio for each muscle, muscle activation (A) during each task was qualified according to muscle specific primary moment arms, 'in-phase' (IP) or 'out-of-phase' (OP) with respect to its primary moment arm and the specific Activation Ratios were calculated by following formula:

$$AR_{muscle} = \frac{A^{IP}_{muscle} - A^{OP}_{muscle}}{A^{IP}_{muscle} + A^{OP}_{muscle}} \quad [-1 \leqslant AR_{muscle} \leqslant 1].$$

The decision to normalize or not normalize is based on the type of descriptions or comparisons that researchers want to be make. If subjects are their own control and contrasts are made on the same muscle within a day, without removing the electrode, normalization is not a big deal. But if comparisons are made between subjects, days, muscles, or studies, the normalization process is required. Most studies on normal population are using MVIC for normalization of the EMG data. But EMG studies in patient population have used different normalization methods and therefore, the comparison between different reports is highly challenging.

2.4.2 EMG and Muscle Force

The EMG-force relationship of skeletal muscles has been a topic of interest and controversy in biomechanics for few decades. In fact, two main control strategies adjust the contraction process and modulate the force output of the involved muscle and therefore, influence the magnitude and density of the observed signals: "Recruitment of MUAPs" and "Firing Frequency"[168] An increase in the firing rates of motor unit is known to increase force and the integrated form of the EMG (IEMG)[170] and recruited of an increasing number of motor units also increases muscular force and the corresponding IEMG.[198] Hence, there must be at least a qualitative relationship between the EMG signal and the corresponding force of the muscle. EMG-Force relations of skeletal muscles have been described for isometric contractions[199-201] and both linear and non-linear relationship of EMG-Force in different skeletal muscle have been reported.[195,202] Muscles that use motor unit recruitment to obtain the initial 50% of their maximal force, and use firing rate increase to complement the remaining 50%, have a nearly linear EMG-force relationship. Muscles that use recruitment to obtain 60% and up to 100% of their maximal force demonstrate progressive increase in non-linearity of their EMG-force curves.[203] Generally, small muscles recruit all their motor units below 50% of their maximal voluntary contraction and larger muscles recruit motor units throughout the full range of voluntary force. So smaller muscles rely on firing rate and larger muscles rely primarily on recruitment to modulate their force.[170] It is not clear if force production of rotator cuff muscles is more dependent on the firing rate or recruitment control strategy. But increasing in EMG activity of rotator cuff muscles may qualitatively indicate higher level of force generation and hence, stress within those muscles.

Disselhorst-Klug et al. (2009)[204] in their review study claimed that rather than anything else, muscle force can be estimated from EMG signals in geometrically well-defined situations during isometric contractions of limb muscles. However, the effects of muscle length and the elastic properties of the muscle tissue, the tendons and the ligaments should be taken into consideration. In addition, it should be considered that EMG characteristics and its relationship to force may change with muscle fatigue. With fatigue, muscle force decreases while EMG activity may show different patterns of unchanged, increasing or decreasing.[205]

For dynamic contractions, the EMG-force relationship is more complicated and the additional factors such as type of contraction, contraction velocity or contributions of other muscles to the resulting movement become important. It has been shown that for a given force generation, less motor unit activation is required for eccentric compared with concentric contractions. Therefore, EMG amplitude associated with negative work (muscle lengthening) is considerably less than that associated with the same amount of positive work (muscle shortening).[206] Bigland et al.(1954)[207] showed surface EMG amplitudes for eccentric contractions of the plantar flexors to be approximately 50% of concentric contractions at similar force levels. Similar results have been demonstrated in the elbow flexors (eccentric EMG 56% of concentric) [208]. Therefore, EMG in regard to muscle force should be interpreted cautiously.

However, the main focus in clinical studies is different from biomechanical studies. Biomechanical studies aim to quantitatively measure the amount of force produced by a muscle, and EMG may not be a reliable tool for this measurement. Clinical studies have more qualitative approach and aim to identify the exercises that might produce more or less muscle force and compare them with each other. Clinical studies do not care how much force a muscle exactly produced; they search for the possibility of higher or lower stress within the muscle that may be caused by bigger or smaller force generation respectively. In rehabilitation studies, the assumption is when a muscle has higher activity, then, it may be under higher stress. EMG findings have been consistent with clinical experiences. For example, lower EMG activity has been reported for the exercises of early phase of rehabilitation than the latter phases.[7] All the discussions that will be presented in the following chapters are based on this assumption.

2.4.3 EMG and Injured Muscle

Theoretically, tissue damage may affect EMG contents through different mechanisms as suggested by Edgerton et al. (1996).[209] First, tissue damage may stimulate pain receptors and the nociceptive input to the spinal cord may alter the excitation levels of multiple motor neuron pools. This latter may result in alteration of motor neurons recruitments and amplitude of EMG signals. Second, a ruptured or weakened muscle fiber will cause a reduction in force generating capacity and may also result in reduced EMG activity (**hypoactivity**). On the other hand, the nervous system can apparently detect a reduced capacity to generate force from a specific muscle or group of muscles and compensate by recruiting more motor neurons. This compensation can be made by recruiting more motor units from an un-injured area of the same muscle or from other muscles. Synergistic muscles would be recruited to compensate, leading to an unusually high level of motor neuron activity in these muscles (**hyperactivity**). Since the recruitment of some motor neurons pools would increase while the other decrease, the change of the ratios of the amplitude of EMG from the affected pools would be readily apparent. Finally, a conscious or subconscious re-education of the motor system is another mechanism that can explain EMG alteration. With a persistent injury, patients learn or acquire new ways to perform a task that enable them to avoid using musculature that is directly associated with the tissue injury. Neural adaptations may also occur with a chronically stretched tendon or muscle unit because faulty feedback on the forth-length-velocity relationship could decrease the load the muscle would support. Chronic compensation could also affect the spinal reflex pathways causing Golgi tendon organ pathways to become desensitized.

All the above explanations can be applicable for the changes of EMG activities in the injured rotator cuff muscles. Following rotator cuff tear, different types of modification in RC muscle integrity have been reported. The development of fatty infiltration and muscle atrophy of the rotator cuff musculature is a clinical problem even after surgical treatment of chronic rotator cuff tendon tears.[210] In an animal study it has been shown that with tendon disruption, the muscle fibers shorten and there is an increase in the pennation angle, allowing fat to be deposited within the interstitial spaces between the muscle fibers.[211] Interestingly the muscle changes that occur following chronic cuff tears differ from that observed following suprascapular neuropathy, especially with respect to the muscle border, and overall distribution of fat infiltration.[212] In addition, massive rotator cuff tears may be associated with suprascapular neuropathy. A cadaveric study suggested that retraction of the supraspinatus muscle after a large rotator cuff tear changes the course of the suprascapular nerve through the suprascapular notch, potentially creating increased tension on the nerve and placing the nerve at risk for injury.[213] This hypothesis supported by an EMG study on eight subjects with massive rotator cuff tear, all had supra-scapular neuropathy.[214]

As mentioned before, pain by itself can affect muscle activation pattern. Lund et al. (1991)[215] in their pain-adaptation model showed that pain increased the activity in the antagonist and decreased the activity in the agonist muscles during voluntary movement. Another study[216] showed that acute pain provoked by either subacromial or intra-supraspinatus saline injection caused increased activity of latissimus dorsi (antagonist) to protect the painful structures. This finding has been previously reported in patients with massive cuff tears who had higher adductor (pectoralis major, latissimus dorsi, teres major) activation during arm elevation.[217] Interestingly, after subacromial lidocaine injection in those symptomatic shoulders, 5 out of 8 patients restored partly this aberrant activity in one or more of their adductor muscles. Altered shoulder muscle activity pattern in symptomatic patients with cuff tear indicates different motor patterns and neuromuscular strategies in these patients. All the above facts should be taken into consideration when a study on patient population is designed. In fact, the muscle activity pattern in a shoulder with chronic rotator cuff tear may be different from the one with acute tear. Likewise, symptomatic patients may have different activation pattern comparing to asymptomatic patients. So, in our third study on patients with rotator cuff tear, we tried to harmonize the sample group with symptomatic patients who had chronic full thickness rotator cuff tear.

2.4.4 **What EMG can and cannot tell us**

It is important to adjust our expectations from what EMG can provide for us. EMG can qualitatively tell us if a muscle is active or not (on/off) and in which phase of time within a movement (quantitatively). EMG can qualitatively show if a muscle is more or less active but can quantitatively estimate how much a muscle is active based on MVIC reference. EMG can also estimate muscle fatigue in repeated trials by detecting the changes in frequency spectrum of muscle activity.

More specifically in shoulder studies, EMG can help us to understand the appropriate activation pattern of the shoulder musculature which is required to control and stabilize the shoulder joint during different movements. Shoulder stability is highly relied on the contribution of its muscles. While the muscles must have appropriate strength and endurance to generate and sustain appropriate tension, it is also necessary for the contraction of the muscles to be appropriately controlled. If contraction of a muscle is initiated too late, too slowly, or too little, then its contribution to shoulder control may be compromised. Hypothetically such a change in recruitment strategy may lead to compromised protection of the shoulder structures. As deliberated before, EMG should not be equated to shoulder muscles or joint forces. However, in well-designed situation, EMG may estimate the force level and muscle stress.

2.4.5 EMG studies on shoulder musculature

A summary of EMG studies on shoulder musculature, related to the first phase of rehabilitation is presented in Table 5. Different methods for EMG studies on shoulder musculature are usually used in the literature. A more practical method is to compare EMG activity of one muscle across different exercises and express the EMG signals relative to a common reference such as the percentage of MVIC. To help generalize the comparison of muscle activity, an arbitrary classification based on MVIC normalization has been accepted as a method of quantifying the activity level of a muscle in most rehabilitation studies.[14,218-220] In this method 0–20% MVIC is considered low muscle activity, 21–40% MVIC moderate muscle activity, 41–60% MVIC high muscle activity, and > 60% MVIC is considered very high muscle activity. Although this classification is not highly precise, it has valuable application in clinical studies. For example, early after rotator cuff surgery the recovering patient is recommended to avoid exercises that generate moderate to high rotator cuff activity to avoid stressing the healing tissues. We followed this method to quantify the muscle activity of the shoulder musculature and identify the safety of the rehabilitation exercises in two studies of this dissertation.

It can be noticed that most of these studies have been performed on normal subjects, because EMG studies on patients with shoulder pathology have some limitations. For example, cuff patients may not be able to create a real MVIC; some exercises may not be safe enough to be evaluated in patient after cuff repair; and controlling or harmonizing all the influencing factors on tendon pathology or healing may not be feasible in patient population. These limiting factors caused that many of shoulder rehabilitation exercises being evaluated in normal population.

Table 5 : EMG studies related to the first phase of rehabilitation after rotator cuff repair

A: Immobilized shoulder

Authors	Subjects	Protocol	Results	Comments
Vaughan et al.[221] 1989	6 healthy subjects	Non-dominant upper limbs immobilized in a plaster cast for 14 days. Isometric muscle strength of elbow flexors and extensors + IEMG output of the agonist, antagonist were measured	Decrease in flexor strength of the casted limb. Antagonist IEMG amplitude was decreased during flexion, and agonist IEMG amplitude and antagonist IEMG amplitude were diminished during extension of the casted limb.	Short-term upper limb immobilization affects elbow flexion strength and some IEMG characteristics during a ballistic forearm movement.
Yue et al.[22] 1997	10 healthy subjects	Non-dominant elbow was immobilized at a 90° for 4 w with a fibre-glass cast. Measurements: CSA of the flexor muscles by MRI; MVC by EMG	Decrease in CSA and volume of the flexors by11.2 + 3.1 %. Decline in MVC by 35.1 + 16-6 % in day 1, and 16.6 + 16.5 % in day 2 post-immobilization Pre-immobilization level after 2 w	4 w elbow caused significant reduction in the CSA and MVC force of the elbow flexor muscles.
Smith et al.[222] 2004	6 healthy Men	EMG activity from each immobilized muscle at rest and during slow, fast, and resisted contralateral upper limb motions (5, 15, and 25 lb).	Slow contralateral upper limb motions: <15 % MVC for SS, IS Fast contralateral upper limb motions: 56.7% MVC for IS during a fast straightforward reach. 25.2%-32.1% MVC for SS during all resisted backward-pulling motions.	Contralateral upper limb motions at self-selected speeds and cross-body, straightforward, or downward reaches at either a slow or fast speeds may be appropriately prescribed while the shoulder remains immobilized.
Smith et al. [13] 2006	5 healthy men	EMG recording of immobilized shoulder muscles during scapular clock, counter-clock rotations, elevation,	Upper SC activity was uniformly high (40%−63% MVC).	1-scapular depression and protraction exercises could potentially be safe after rotator cuff repair.

		depression, protraction, and retraction exercises.	Scapular depression and protraction: <20% MVC for SS and IS.	2- All exercises studied should be avoided after SC repair.
Smith et al. [223] 2007	5 healthy men	EMG activity of immobilized shoulder muscles during a split-stance cross-body rotation (twisting to the opposite side at high, mid, and low levels), split stance attempted ipsilateral floor touch, and attempted overhead reach.	For all exercises, biceps and IS activity was <10% MVC, whereas upper SC activity was (29%−68% MVC). SS activity was <20% MVC for all motions except the attempted overhead reach (23% MVC).	Selected kinetic chain exercises could potentially be implemented during periods of shoulder immobilization
Farthing et al.[224] 2008	30 healthy	1) (Cast-Train) wore a cast (left side) for 3 w and trained the free arm by maximal ulnar deviation 5days/w. 2) (Cast) wore a cast and did not train. 3) Control. Muscle thickness (US), muscle strength (dynamometer), EMG of Flexor Carpi Ulnaris, and Extensor Carpi Radialis were measured.	No change in muscle thickness and strength in immobilized limb in cast-train while reduction of both factors in cast group. The agonist muscle showed a significantly higher amplitude of activation compared with the antagonist muscle.	Strength training of the free limb attenuated strength loss in the immobilized limb during unilateral immobilization. Strength training may have prevented muscle atrophy in the immobilized limb.
Magnus et al.[225] 2010	25 healthy	1) left hand immobilized + right hand strength training; 3 times/day 2) immob + not strength training; 3) no treatment Torque (dynamometer), muscle thickness (US) and muscle activity (EMG) of biceps and triceps were measured.	Thickness of both left biceps and triceps was significantly greater in immob + training group. Right and left elbow extension strength for Immob + Train was significantly different from the respective limb of Immob.	Strength training of the non-immobilized limb benefits the immobilized limb for muscle size and strength.

Kuhtz-Buschbeck and Bo Jing [226] 2012	20 healthy	Surface EMG of shoulder muscles during walking on a treadmill 1) with natural arm swing (normal) 2) while holding the arms still (Held), 3) with the arms immobilized (Bound), and 4) with the arms swinging opposite-to-normal phasing (Anti-Normal).	Immobilization of the right arm with a brace did not completely abolish activity of shoulder muscles and posterior deltoid, trapezius and LD showed EMG signals. PM was more active in bound than normal condition.	some EMG signals persisted when the arms were immobilized during walking

B: Passive/Active ROM Exercises

Authors	Subjects	Protocol	Results	Comments
McCann et al.[7] 1993	10 healthy	EMG of nine shoulder muscles including SS and IS during three phases of shoulder rehabilitation exercises as described by Neer.[36]	Phase I (passive) exercises performed in the supine position showed the least EMG activity.	Supine Phase I exercises should be considered in the early postoperative period after shoulder surgery to achieve maximum motion while minimizing shoulder muscle activity.
Dockery et al.[218] 1998	10 healthy	The activity of SS, IS, trapezius and AD were measured during CPM, Pulley pendulum, self-assisted bar-raise, self-assisted IR and ER, Therapist assisted scaption, IR and ER	For all muscles, Pulley exercises showed more activity than CPM. SS activity: 17.6%MVC for pulley, 8.7%MVC for self-assisted bar raise, 5% MVC for CPM. Therapist assisted was similar to CPM.	CPM and therapist assisted passive ROM may increase the safety margin.
Guant et al. [227] 2003	15 healthy	EMG of SS, IS and AD assessed during AAROM exercises to regain patients' active forward elevation.	IS and SS demonstrated increasing trends in EMG activity from gravity minimized to upright assisted.	EMG activity in all gravity-minimized exercises are low and would thus be used in the earliest

		Elevation exercises were divided into 3 types: 1) gravity minimized, 2)upright assisted, and 3) upright active.		stage of a rehabilitation continuum to regain active motion
Wise et al.[228] 2004	20 Healthy	Activity of SS, IS, PD, AD and PM during arm elevation in 1) vertical wall slides (short lever), 2) diagonal wall slides (45° angle) (long lever) in two conditions: their hand in contact with the wall supported) and not in contact with the wall (unsupported).	Greater SS activity in the unsupported exercises versus the supported exercises. Exercises performed in the 45° diagonal position were more demanding on shoulder musculature	Supported short lever arm AROM exercises should precede unsupported long lever arm AROM exercises.
Ellsworth et al.[229] 2006	9 subject with shoulder pain, 17 healthy	EMG of SS, IS, UT, MD during Codman's pendulum exercises 1) wrist suspended 1.5 kg weighted-ball, 2) hand-held 1.5 kg dumbbell, 3) hand-held 1.5 kg weighted-ball, and 4) no weight was recorded.	Generally, SS /upper trapezius muscle activity (17% MVIC) was significantly higher than deltoid (6%) and infraspinatus (7%). pathological group had significantly greater muscle activity in IS and SS. No effect of weight for upper trapezius and IS.	Patients with shoulder pathology had greater difficulty relaxing their SS /upper trapezius muscle group during Codman's pendulum exercises.
Uhl et al.[230] 2010	10 healthy	EMG of SS, IS, AD, UP, LT, and SA, during 2 passive, 4 active –assistive and 6 active exercises	No significant difference between passive and AAROM exercises, in both SS and IS activities were <20% MVC. The standing shoulder active exercises demonstrated an increase in SS activity to the moderate category.	Progression from passive to active-assisted can potentially be performed without significantly increasing muscular activation levels. Upright active exercises should be prescribed later in a rehabilitation program.
Long et al.[231] 2010	13 healthy	EMG of SS, IS, and deltoid muscles while doing pendulum exercises incorrectly and correctly in both large	SS activity: >15%MVC in incorrect and correct large pendulums. Greater activity during	Larger pendulums may require more force than is desirable early

		(51-cm) and small (20-cm) diameters, and while typing, drinking, and brushing their teeth.	large, incorrect pendulums than correct one. >20% MVC during water drinking from a bottle.	in rehabilitation after rotator cuff repair
Murphy et al.[196] 2012	26 patients after surgery	Within the first 4 days after subacromial decompression with/or distal clavicular resection, muscle activity was recorded during 14 exercises of the passive phase of rotator cuff protocols and compared with EMG of the baseline (BL).	SS remained at BL level during therapist- and self-assisted ER, therapist-assisted elevation, pendulums, and isometric IR and adduction. IS was activated > BL for all 14 exercises studied.	Of the 14 exercises studied, 6 allowed SS and 0 allowed IS to remain as passive as quiet-stance baseline in this patient group.

MVC= Maximal Voluntary Contraction, CSA= Cross Sectional Area, ROM= Range of Motion, AROM= Active ROM, AAROM= Active Assisted Range of Motion, CPM= Continuous Passive Motion, US= Ultrasound, AD= Anterior Deltoid, MD= Middle Deltoid, PD= Posterior Deltoid, UT= Upper Trapezius, LT= Lower Trapezius, PM= Pectoralis Major, SA= Serratus Anterior, LD= Latissimus Dorsi, SS= Supraspinatus, IS= Infraspinatus, SC= Subscapularis, w= week, d= day, immob= immobilization

In general, comparing muscle activity between studies is limited by different positioning of electrodes, surface versus indwelling electrodes, varying signal processing techniques, differences in MVIC determination, the use of different normalization methods and different types and speed of contraction. It is also difficult to compare muscle activity between studies when different exercise intensities are applied. In addition, some studies performed statistical analysis while the others did not, and without statistics, interpreting of muscle activity among exercises is very challenging. Despite all these limitations, valuable information can be extracted from EMG studies that can be applied in rehabilitation protocols.

However, from the studies presented in Table 5, some conclusive findings can be extracted: first, EMG studies concerning the immobilization period after rotator cuff repair are very few. Only Smith et al.[13,222,223] studied some exercises that could be theoretically performed with the immobilized shoulder. Second, none of the studies on immobilized shoulder, evaluated the extent of upper limb immobilization in respect to elbow and wrist joints. However, the deteriorating effects of elbow immobilization on elbow flexors strength and CSA have been reported.[22,221] Third, only one study[231] evaluated shoulder muscle activity during a few daily living tasks while the subjects' shoulders were immobilized. EMG studies on rotator cuff muscles during daily living activities are very scarce. Forth, most studies evaluated the exercises that have been routinely used in clinical practices. These exercises included passive ROM, CPM, pendulum exercises, active assisted ROM and active ROM. It means that these EMG studies provided scientific basis for clinical experiences and few innovations in early rehabilitation protocols have been introduced. Fifth, rotator cuff muscles activities during most passive and active assisted ROM exercises were below 20% MVIC and lower muscle activity was interpreted as lower muscle stress in the related studies. Therefore, passive exercises that created lower rotator cuff muscle activity were considered safe post rotator cuff tendon repair. Sixth, active ROM exercises increase the activity of cuff muscles and are prescribed later in rehabilitation program.[230] However, the safe elevation angles and appropriate sequences of elevation planes have not been studied. Seventh, active assisted exercises[230] and supported arm elevation[228] minimally activate the cuff muscles. So, theoretically a supported active arm movement (e.g. by a wedge shaped foam) is applicable in the early phase of rehabilitation.

Considering all the above findings, the objective of this dissertation is presented in the following section.

2.5 OBJECTIVES

The first objective of this thesis is to evaluate the EMG activity of shoulder musculature during some exercises and daily living tasks that can be performed during the early phases of rehabilitation after rotator cuff repair. The immobilization of upper limb is usually not limited to shoulder joint; elbow and wrist joints are also immobilized during this period. There is no report about the activity level of rotator cuff muscles during elbow and wrist exercises and whether or not immobilization of these two joints could be beneficial for repair integrity. We hypothesized that any activity related to elbow and wrist movements would not highly activate rotator cuff muscles. These activities include daily living tasks, such as typing or writing and some light weight training exercises. If it is accepted that any exercise that creates low rotator cuff activity can be considered safe, then immobilization of elbow and wrist joints may not be necessary. In addition, tension on the repaired tendon is controlled by shoulder immobilization and elbow and wrist mobilization would not cause any rotator cuff tendon elongation or tension. To test this hypothesis, a special type of orthosis is needed that can immobilize the shoulder joint while elbow and wrist are mobile. Fortunately, the orthosis was prepared by assistance of Medicus orthopedic laboratory (Laboratoire Orthopédique Médicus) for our studies. This orthosis has three characteristics: 1- the shoulder can be immobilized in scaption position, 2- elbow is mobilized in horizontal plane and wrist can be mobilized in all ROM. 3- the degree of arm abduction is adjustable. The orthosis is light and can be fixed in pelvis. The subjects are then able to perform different exercises and daily living tasks.

The second objective is to evaluate the effect of some resistance exercises of elbow and wrist joints on rotator cuff muscle activity. We hypothesized that strength training of arm and forearm muscles with light dumbbells would not result in high activity of rotator cuff muscles and can be performed in the early phases of rehabilitation rather than three months postoperatively. To have an estimation of the effect of a more strenuous activity, we test maximal forceful gripping, assuming that it would highly activate rotator cuff muscles.

The third objective is to test some active exercises for shoulder and scapula. Active assisted ROM exercises usually begin after week 4 to 6 post-operatively. Although active ROM exercises are generally discouraged in the first phase post repair, the evidence to support this idea is scarce. If it is accepted that rotator cuff is mostly involved in arm abduction and internal and external rotations, then adduction in some angle ranges that impose less stress on the repaired tendon, would not highly activate the rotator cuff muscles. To test this hypothesis, the hard wedge of the shoulder orthosis of Ottobock is replaced by foam wedges with different densities. So, the subject can do supported adduction with different forces compatible with the foam density and then passive abduction will follow.

All the above hypotheses are tested on normal population, as the safety level of such exercises in patient population is not clear and due to all limitations for study on patients which have been previously discussed.

Our **forth objective** is to evaluate the shoulder muscle activity pattern in patients with rotator cuff tears during arm elevation in different planes. Restoring active arm elevation is an important goal of rehabilitation, which is expected to be achieved in 8-12 weeks post-operation. Our last study intends to evaluate the effect of elevation plane and angle on EMG activity of rotator cuff muscles. We hypothesized that in patients with rotator cuff tear, the EMG activity of shoulder musculature during active arm elevation would significantly change with elevation plane and in accordance with the elevation arcs. To evaluate the exact arc of elevation, a 3D motion analysis system is used to measure the glenohumeral elevation angle.

EMG studies have been the scientific basis for many rehabilitation exercises. We believe that the results of our studies will increase the understanding of rotator cuff activity pattern during different tasks and exercises and can be helpful in designing more appropriate rehabilitation program for patients with rotator cuff pathology.

3 STUDIES

3.1 EMG OF AN IMMOBILIZED SHOULDER WHILE ELBOW AND WRIST ARE MOBILE.

Two main hypotheses were evaluated in this study:

1) Elbow and wrist motion would not highly activate rotator cuff muscles

2) Some daily living tasks that involve elbow and wrist movements would not highly activate rotator cuff muscles.

This study was published in the journal of Shoulder and Elbow Surgery under the title of "Electromyographic activity in the immobilized shoulder musculature during ipsilateral elbow, wrist and finger movements while wearing a shoulder orthosis" in October 2013.

The on line version can be found in the following link:

http://www.sciencedirect.com/science/article/pii/S1058274613001973

All the authors were involved in development of the research idea with more input from Dr. Patrice Tétreault, Mickael Begon and Talia Alenabi. Data collection and analysis of data was performed by Talia Alenabi. Monique Jackson enriched the article by her comments and critics as well as English editing. The article was revised several times by all the co-authors. The article has been peer- reviewed and all the questions of reviewers were deliberately responded.

Electromyographic activity in the immobilized shoulder musculature during ipsilateral elbow, wrist and finger movements while wearing a shoulder orthosis

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The authors have no conflict of interest to disclose. The study was approved by the university research ethics committee (Comité d'éthique de la recherche en santé, certificate number CERSS # 2010-1013-P).

ABSTRACT

Background: Shoulder immobilization after rotator cuff surgery is usually prescribed to protect the repaired tendons, however, shoulder orthoses often also immobilize the elbow and wrist joints. There is insufficient evidence to support that elbow and wrist movements can affect repair integrity by highly activating the rotator cuff muscles. The aim of this study was to quantify the electromyographic activity of immobilized shoulder muscles during elbow, wrist and finger movements.

Method: Fifteen shoulder muscles of the dominant limb of 14 healthy subjects were evaluated using electromyography with 11 surface electrodes and 4 fine wire electrodes in the rotator cuff muscles. Whilst wearing a custom orthosis the subjects completed tests involving elbow, wrist and finger movements of the ipsilateral limb. The peak activity of each muscle was normalized to maximal voluntary contraction (% MVC) and averaged across the subjects.

Results: Rotator cuff muscles were activated to less than 10% MVC in both slow and fast elbow flexions. The mean peak activations of all muscles during wrist and finger movements were less than 5% MVC. In daily activities such as writing, typing, clicking a computer mouse, holding a box or bag, rotator cuff muscle activity did not exceed 11% MVC, but sudden movements such as grasping a bottle could show higher levels of activity, that in some individuals exceeded 20% MVC.

Conclusion: Elbow, wrist and finger movements could minimally activate the rotator cuff muscles when the shoulder is immobilized with an orthosis.

Keywords: rotator cuff, immobilization, electromyography, shoulder, orthosis

INTRODUCTION

Shoulder rotator cuff injuries are highly prevalent[45] and re-tears after surgical repair are also common with numerous studies reporting re-tear rates of above 25%.[1, 15, 27, 28] Thus, it is important to protect the repair during the immediate post-operative period, and therefore patients who undergo rotator cuff surgery are often immobilized in a sling or abduction orthosis. However, commercially available shoulder orthoses often immobilize not only the shoulder but also the elbow and the wrist. The effect of elbow and wrist movements on rotator cuff muscle activity has not been studied, and as such there is no data to support that movement of these joints can be detrimental to repair integrity. Since it is known that shoulder muscles are co-activated during some elbow and wrist motor tasks[17, 46] it is of interest to determine if such tasks highly activate the rotator cuff muscles.

Post-operative rehabilitation protocols aim to balance between deconditioning and stiffness[4, 23, 38] that may be related to immobilization,[21, 37] and the harmful effects of over activity on the repaired tendon.[35] Excessive activation of the rotator cuff muscles after surgery may contribute to re-tearing of the tendons,[16, 32] whilst joint stiffness has also been shown to be unfavorable for recovery.[23] Post-operative protocols should therefore be designed to retain joint mobility whilst safely loading the repaired tendons.

The main goal of this study was to quantify immobilized shoulder muscle activity while healthy subjects performed ipsilateral elbow, wrist and finger movements, and determine the effect of speed for some active mobilization exercises. Although muscle activity cannot be directly linked to the level of the potentially damaging force that the rotator cuff must withstand, we considered that electromyography can provide an estimation of the stress levels imposed on the rotator cuff muscles. We hypothesized that immobilized shoulder muscle activity during elbow, wrist, and finger movements would be low, and that daily activities, which involve the elbow, wrist, and fingers, would also minimally activate the rotator cuff.

METHOD

Subjects

Fourteen healthy volunteers (10 men, 4 women; 12 right handed, 2 left handed; 25 ± 4 years; 73.4 ± 9.5 kg; 1.74 ± 0.08 m), free from shoulder and neck disability as determined by the DASH questionnaire[(24)] took part in the study after giving informed consent. All subjects exhibited full, pain free, shoulder range of motion. The study was approved by the university research ethics committee (Comité d'éthique de la recherche en santé, certificate number CERSS # 1013(1)).

Electrode placement

EMG signals were recorded from 15 shoulder muscles of the dominant limb using 11 surface electrodes and 4 fine-wire electrodes. Rectangular silver-silver chloride bipolar surface electrodes (20 mm inter-electrode distance, CareFusion, USA) were placed over the long head of the triceps, biceps, anterior deltoid, middle deltoid, posterior deltoid, latissimus dorsi, sternal pectoralis major, serratus anterior, upper trapezius, middle trapezius and lower trapezius using standard placement techniques.[(3, 13, 39)] Fine-wire intra muscular electrodes (30 mm, 27 gauge, CareFusion, USA) were inserted into the supraspinatus, infraspinatus and teres minor as described by Perotto & Delagi[(36)] and into the lower subscapularis as described by Kadaba et al.[(25)] using standard aseptic techniques. The ground electrode was placed on non-dominant clavicle. Proper electrode placement was confirmed by checking the signals during sub-maximal isometric contractions which were performed in specific positions expected to generate high EMG activity.

Maximum voluntary contraction tests

A total of 14 tests (common test for infraspinatus and teres minor) were performed to elicit maximum voluntary contractions (MVC) from the 15 muscles[(3, 5, 13, 39)] (Table 1). The movements were shown and explained to the subject prior to completion, and a pre-trial with minimal force was used to ensure the movement was correctly performed. Each contraction was performed for 5 s, with a gradual increase in force over the first second, a sustained maximum for three seconds, and a gradual release over the final second. Two repetitions of each test were performed, with a minimum rest interval of 30 s between repetitions. The subjects were closely monitored for proper positioning and when the positioning was incorrect the trial was repeated. The test order was randomized by subject position (seated or lying), and a minimum of 1 min rest preceded each new test position.

Table 1: Short description of the MVC tests

	Muscle	**MVC Test**
1	Upper Trapezius	Neck bent to the side, rotated to the opposite, neck extension is resisted [13].
2	Middle Trapezius	Shoulder abduction at 90° in prone position is resisted[13].
3	Lower Trapezius	Arm raised above the head, shoulder flexion in prone position is resisted[13].
4	Anterior Deltoid	shoulder forward flexion at 90° is resisted[5]
5	Middle Deltoid	Shoulder abduction at 90° is resisted[5].
6	Posterior Deltoid	Shoulder extension of an abducted shoulder (90°) in prone position is resisted[5].
7	Biceps (long head)	Elbow flexion with supinated forearm is resisted[39].
8	Triceps (long head)	Elbow extension in a flexed elbow (90°) is resisted[39].
9	Latissimus Dorsi	Shoulder adduction with an abducted shoulder (90°), flexed elbow is resisted[5].
10	Pectoralis Major (Sternal)	Horizontal adduction of the shoulder in supine position is resisted[5].
11	Serratus Anterior	Resistance is applied above elbow and at scapula in a flexed shoulder (125°)[13].
12	Supraspinatus	Shoulder abduction in a lying side position is resisted[5].
13	Infraspinatus	Lateral rotation in a lying side position is resisted[5].
14	Teres Minor	
15	Lower subscapularis	Lift off test in prone position[5].

Immobilization

The dominant shoulder was immobilized using a custom orthosis (Figure 1), that elevated the arm in the scapular plane. The orthosis, which weighed approximately 0.8 kg was a pre-production prototype, and as such has not yet been tested on a patient population. The orthosis supported the forearm between the elbow and wrist, and was fixed to the waist using a belt. The length of the support bar between the elbow and the waist could be adjusted so as to abduct the shoulder whilst supporting the forearm. While wearing the orthosis the subject could flex and extend their elbow in the horizontal plane (see Figure 1), flex, extend and rotate their wrist, and move their fingers.

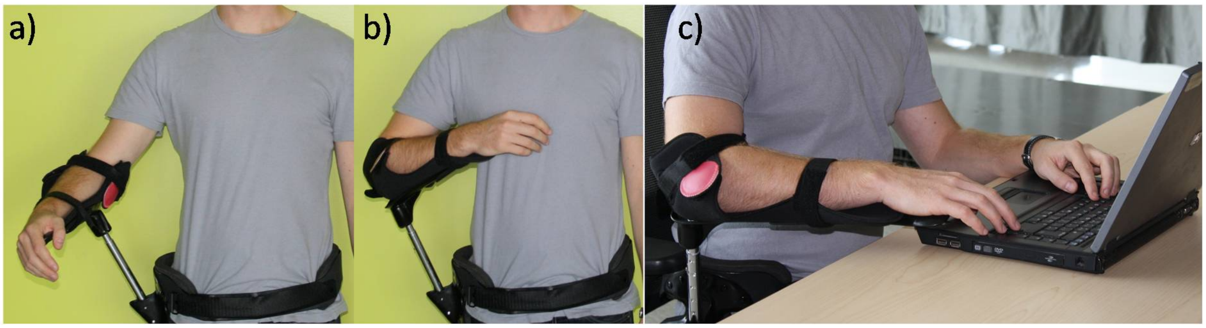

Figure 1: Shoulder immobilization while wearing the orthosis with a) elbow extended; b) elbow flexed; c) in sitting position.

Tests

The subjects completed a number of tests using the ipsilateral upper limb while wearing the shoulder orthosis. Where applicable a metronome was used to control the pace of the movements, and there was one minute rest between tests. The tests were performed in two sets namely elbow, wrist and finger movements (Table 2) and ergonomic daily living tasks (Table 3).

Table 2: Elbow, wrist and finger movement tests

Joint	Movement	Speed
Elbow	10 cycles of Extension-flexion in the horizontal plane	30 and 60 cycles/min
Wrist	10 cycles of Extension-flexion	30 and 60 cycles/min
	10 clockwise rotations	60 rotations/min
	10 counter-clockwise rotations	60 rotations/min
Fingers	10 cycles of making a fist gently and extending the fingers	20 and 30 cycles/min

The subject starts each test in a standing position with the elbow extended except for the elbow movements where the elbow is initially in the flexed position.

Table 3: Ergonomic daily living tasks

Starting position	**Movement**	**Note**
Sitting upright without back support, in front of a table adjusted to the subjects preferred height	Writing “a-z” and “ 0-9” with pencil on a piece of paper	Normal speed
	Typing a text of 80 words on a laptop using both hands	Normal Speed
	Playing two Clicking games. In the first game the subject clicks 3 times rapidly before changing mouse position. In the second game the subject clicks once before changing the mouse position. Repeated 10 times for each game.	Clicking games created using Matlab R2011b, The Mathworks, Natick, MA.
Standing, elbow extended	Holding a box with both hands for 5s.	Box: 2.3 kg, 22 x 28 x 5 cm
	Holding the handle of a light plastic bag containing a box, for 5s.	
	10 cycles of catching a bottle by ipsilateral hand when it is thrown by contralateral hand and vice versa. At a speed of 20 cycles/min.	Bottle of water (591 ml).

Data processing

The EMG data were collected and processed using a custom data acquisition program (Matlab R2011b, The Mathworks, Natick, MA). The electrode signals acquired at 4000 Hz were passed through an amplifier (Model15A54, Grass Technology, West Warick, RI) with 10-1000 Hz bandwidth detection for the surface electrodes, and 10-3000 Hz bandwidth detection for the fine-wire electrodes (Common Mode Rejection Ratio > 90 dB; input impedance>20 MΩ; Noise:10 μV peak to peak). The signals were filtered (10th order notch filter at 60, 120 and 240 Hz, and 2nd order Butterworth bandpass filter at 20-400 Hz), and the sliding root-mean square amplitude with 100 ms window calculated and normalized to generate a % MVC for each muscle. Data that was contaminated by noise (less than 5% of the data) was removed and not used in further analysis.

For the tests with cyclic repetitions the peak activation during the six middle cycles was determined, and averaged across the study population. For the continuous movements, such as writing or typing, the peak activation during the complete trial was determined, and averaged across the study population. To determine the muscle activity patterns the means and standard deviations of the normalized EMGs were calculated and demonstrated in graphs. For the tests completed with two different speeds, a repeated measure ANOVA with two factors of muscle and speed was performed. A significant interaction between muscle and speed was found, indicating that particular muscles activated in a particular speed with a greater extent. As there was a significant interaction between factors, paired t-tests were completed for each muscle to check the statistical differences between speeds; $p \leq 0.05$ was considered significant.

Within this study the EMG activity was classified as low (< 20% MVC), moderate (21 – 40% MVC), high (41 – 60% MVC) and very high (> 60% MVC), based on other studies on shoulder muscle activity.[9, 18, 26, 40-42] EMG activity levels below 20% MVC are generally regarded as potentially safe after injury or operation.[10, 20, 31]

RESULTS

Elbow, wrist and finger movements

For the shoulder muscles considered in this study, the mean peak activations were less than 20% MVC (Figure 2a) during elbow extension/flexion in the horizontal plane. The biceps exhibited the highest activity with 12.0 ± 5.6% MVC and 17.2 ± 9.0% MVC for slow and fast movements respectively. The rotator cuff muscles were activated to less than 10% MVC in both slow and fast elbow flexion, with the supraspinatus showing the highest activity during both slow and fast movements (9.0 ± 3.7% MVC and 9.8 ± 4.5% MVC respectively). There was a significant difference between the level of muscle activity during slow and fast elbow movements for the middle trapezius ($p = 0.009$), lower trapezius ($p = 0.03$), posterior deltoid ($p = 0.01$), biceps ($p = 0.01$), triceps ($p = 0.03$) and pectoralis major ($p = 0.004$) with faster movement resulting in higher activity.

During the considered wrist movements the mean peak activations of all shoulder muscles were less than 5% MVC (Figure 2b, 2c). Supraspinatus exhibited the highest activity in slow wrist flexion while teres minor exhibited the highest activity in fast wrist flexions (4.0 ± 3.1% MVC and 4.4 ± 2.4% MVC respectively). Teres minor was also the most active muscle during clockwise and counterclockwise rotations (4.6 ± 2.4% MVC and 4.7 ± 2.1% MVC respectively). The effect of wrist movement speed on shoulder muscle activation was only significant for teres minor ($p = 0.01$) and infraspinatus ($p = 0.04$), with higher speed again resulting in higher activation.

During finger extension/flexion the mean peak activations of the shoulder muscles were less than 3% MVC (Figure 2d). The effect of finger movement speed on shoulder muscle activation was not significant.

Ergonomic daily living tasks

When performing basic daily activities, such as typing, writing and clicking a computer mouse, the maximum activations of the shoulder muscles were less than 11% MVC (Figure 3a). In all four activities the rotator cuff muscles exhibited higher activity than the other shoulder muscles.

When holding a weighted box or bag (2.3 kg) the maximum activations of the shoulder muscles were less than 10% MVC, although there was large variability between the muscles (Figure 3b). In the two tests the biceps showed the highest activity (7.4 ± 3.7% MVC for holding the box and 8.5 ± 4.5% MVC for holding the bag). Amongst the rotator cuff muscles the infraspinatus and teres minor exhibited the highest activity whilst holding the bag (7.9 ± 5.6% MVC and 7.5 ± 5.1% MVC respectively), while the supraspinatus exhibited the highest activity when holding the weighted box in two hands (6.1 ± 5.1% MVC).

When catching a weighted bottle the mean peak activations of the shoulder muscles were below 20% MVC (Figure 3c), although there was large variability between the muscles. There was also high inter-subject variability, as seen by the large standard deviations. The biceps exhibited the highest activity with 17.7 ± 9.0% MVC. Compared to the other tasks catching a weighted bottle resulted in high mean peak activations of the rotator cuff muscles with only the subscapularis below 10% MVC.

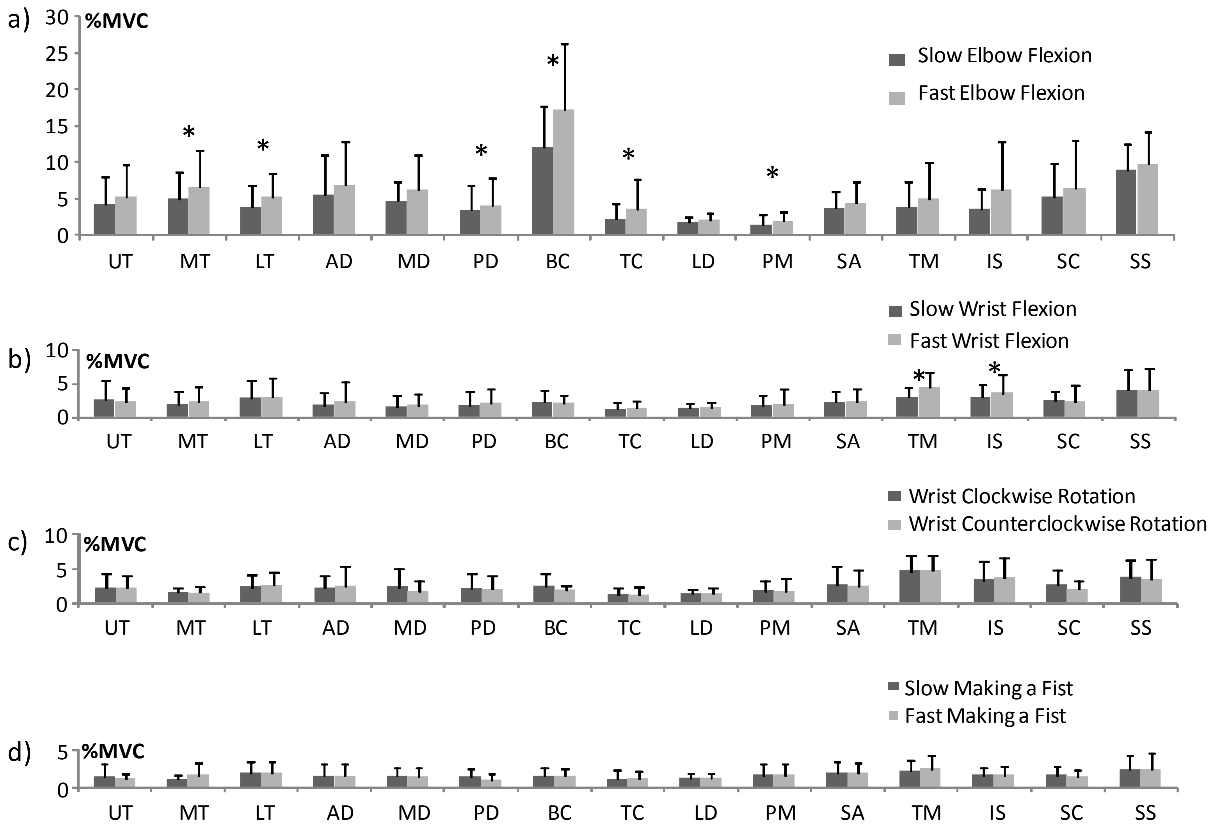

Figure 2: Shoulder muscle activity during a) elbow flexions in the horizontal plane, b) wrist flexions, c) wrist clockwise and counter-clockwise rotations and d) finger movements.

UT=Upper Trapezius; MT=Middle Trapezius; LT=Lower Trapezius; AD=Anterior Deltoid; MD=Middle Deltoid; PD=Posterior Deltoid; BC=Biceps; TC=Triceps; LD=Latissimus Dorsi; PM=Pectoralis Major; SA=Serratus Anterior; TM=Teres Minor; IS=Infraspinatus; SC=Subscapularis; SS=Supraspinatus

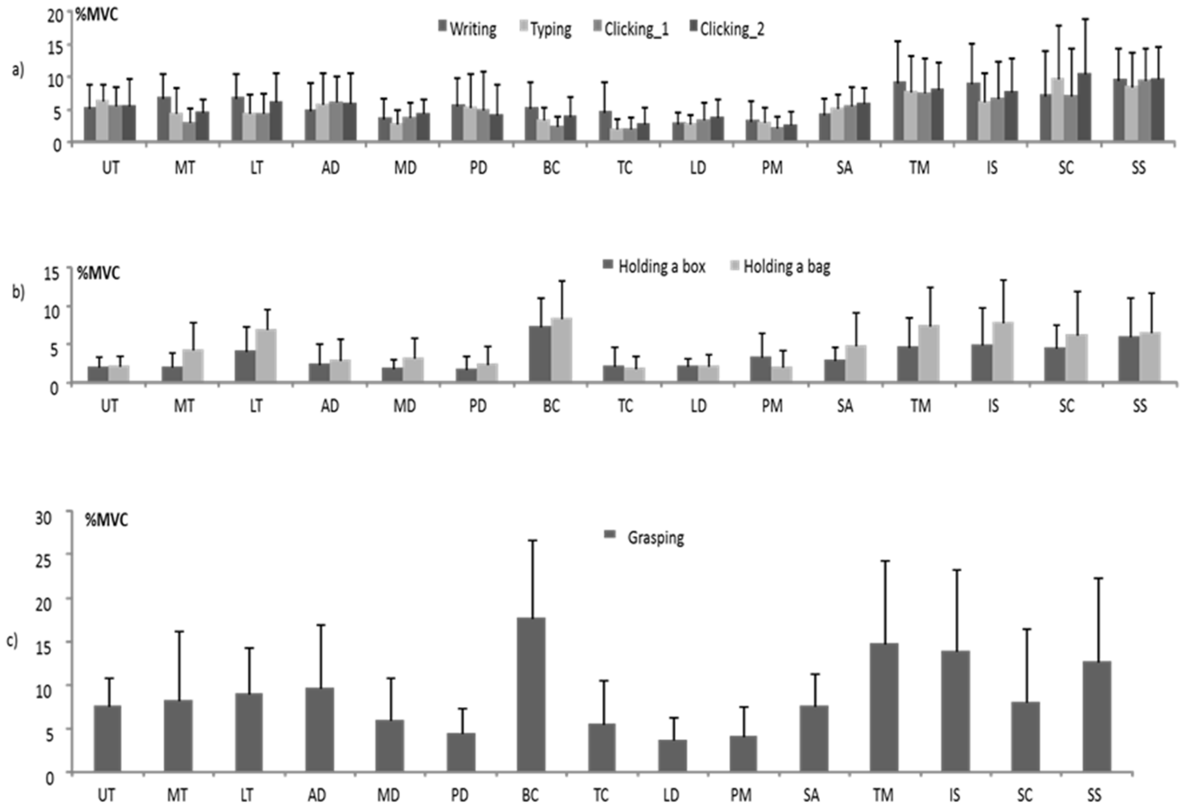

Figure III: Shoulder muscle activity during a) typing, writing and clicking games; b) holding a box and holding a bag; c) grasping a bottle

UT=Upper Trapezius; MT=Middle Trapezius; LT=Lower Trapezius; AD=Anterior Deltoid; MD=Middle Deltoid; PD=Posterior Deltoid; BC=Biceps; TC=Triceps; LD=Latissimus Dorsi; PM=Pectoralis Major; SA=Serratus Anterior; TM=Teres Minor; IS=Infraspinatus; SC=Subscapularis; SS=Supraspinatus

DISCUSSION

The purpose of this study was to identify movements that can be performed during post-operative immobilization without inducing high activation of the rotator cuff muscles. Complete immobilization can lead to joint stiffness,[37, 38] bone loss[30] and muscle deconditioning,[21] which can affect functional outcomes after surgery. It is therefore of interest to identify movements that can be performed while the shoulder remains safely immobilized and that do not induce high levels of shoulder muscle activation. While electromyography (EMG) studies can provide guidelines for post-operative protocols, there are few such studies on the immobilized shoulder. Smith et al.[42] showed that while wearing a shoulder immobilizer contralateral upper limb motions at self-selected speeds were not likely to be harmful to healing tissues. Smith et al.[40] found that isolated scapular depression and protraction motions could produce levels of electromyographic activity sufficient enough for strengthening in the serratus anterior and trapezius muscles while maintaining low levels of electromyographic activity in the supraspinatus and infraspinatus. The same authors also suggested that selected kinetic chain exercises could potentially be implemented during periods of shoulder immobilization.[41] These studies did not, however, address the effect of ipsilateral elbow, wrist and finger motions on the activity level of the rotator cuff and therefore such movements were of interest.

Our results showed that elbow flexion/extension at two different speeds did not highly activate the rotator cuff muscles, with the activity levels remaining below 20% MVC. However, elbow flexion at high speed may elicit biceps activation beyond 20% MVC in some individuals. Biceps pathology is a common evolution of rotator cuff tears.[44] Furthermore biceps tenotomy or tenodesis may be performed concomitantly with rotator cuff repair.[22] Our results showed that high speed elbow movements could moderately activate the biceps, and therefore fast elbow movements may be potentially dangerous when there is concomitant biceps pathology or biceps surgery.

Wrist and finger movements were generally found to negligibly activate the shoulder muscles. Fast wrist flexion/extension may augment activity of the teres minor and infraspinatus, but the activity levels still remained very low (less than 10% MVC). Therefore wrist immobilization post-surgery cannot be rationalized.

During activities of daily living, such as computer use and writing, the rotator cuff muscles were more highly activated than the other shoulder muscles. This finding can be attributed to the contribution of the rotator cuff in shoulder stability.[2, 8] Palmerud et al.[34] showed that the arm posture and hand load can influence greatly the development of intramuscular pressure in infraspinatus and supraspinatus muscles, but the muscle activity pattern was not the area of interest in this study. Our results suggest that despite the higher activity level of rotator cuff muscles during these tests, the activity levels were still low (below 20% MVC).

Furthermore, when the subject was asked to hold a weight, either in one hand or two hands the rotator cuff muscles were again minimally activated. Thus it can be suggested that holding a light weight (2.3 kg) for a short period of time (5 s) may be potentially safe after rotator cuff surgery. However, Smith et al.[42] showed that EMG activity in most but not all immobilized shoulder muscles increased when the resistance on the contralateral upper limb was increased, therefore the activity level may change if the load or time is increased.

Sudden movements such as grasping a bottle can result in higher activity of the rotator cuff muscles. In some of the subjects the activity level went beyond 20% MVC for three of the rotator cuff muscles (supraspinatus, infraspinatus and teres minor) as well as for the biceps. The inter-subject variability can be related to different positions and techniques during this task. Therefore the data suggests that sudden movements would not be safe for all individuals during post-operative immobilization. These results are in accordance with the study of Day et al.[7] which reported moderate activity of rotator cuff muscles in semi-restricted shoulders during internal and external perturbation rotations.

Within this study we assumed that activation of the rotator cuff musculature below 20% MVC, could be considered potentially safe. Although muscle activity cannot be directly linked to the level of the potentially damaging force that the rotator cuff must withstand, an almost linear relationship between EMG signal and isometric force has been shown[11, 12] and furthermore, for dynamic movements EMG activity has also been shown to increase with force.[20] The force to failure of rotator cuff repair has been reported between 191 – 287 N(29), whilst the force generated during a maximal contraction of the rotator cuff has been approximated at 302 N.[6] Thus movements that elicit muscular activity of the rotator cuff of less than 20% MVC, should be well below the force to failure.

Our findings, like those of many other rehabilitation studies [10, 20, 31, 40-43] are based on a healthy population whose shoulder muscle activity may not accurately represent that of patients with rotator cuff repair, since muscle pain can reduce MVC level [19] and EMG activity.[14] However, EMG data is commonly normalized based on MVC levels, and such types of contraction are not safe to assess in a postoperative patient population. Furthermore we considered that the healthy population would exhibit more accurate MVCs and that the muscle activity patterns in different tasks would be less likely to be biased. The authors appreciate that further testing on a patient population is required.

In this study the subjects performed movements of the ipsilateral upper limb whilst wearing the shoulder orthosis. The movements were not forceful and were not resisted. While such activities should prevent stiffening of the joints,[33] resisted movements (for example holding a weight) may also prevent deconditioning. The activity pattern may, however, change if the resistance is increased and therefore the safe range of resistance is unknown. This should be considered in future research.

In summary, the results of this study imply that elbow, wrist and finger movements, and selected daily activities could be considered potentially safe during the post-operative immobilization period, and suggest semi-immobilization instead of full-immobilization of the upper limb after rotator cuff repair. We believe that the results of this study can provide useful information for clinicians, as well as for orthosis designers.

CONCLUSION

Shoulder immobilization after rotator cuff surgery is often required to protect tendons from excessive tension, but no evidence supports that the elbow and wrist should also be immobilized. Our results suggest that movement of these two joints as well as of the fingers could minimally activate the rotator cuff muscles. The results of this study could be used to guide orthosis selection or guide the design of a dynamic shoulder orthosis.

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3.2 RESISTANCE TRAINING DURING SHOULDER IMMOBILIZATION

Three main hypotheses were studied by this project:

1) Light weight training exercises of Elbow and wrist would not highly activate rotator cuff muscles
2) Maximal gripping may provoke high rotator cuff activity.
3) Arm adduction exercises with wedge shaped foams would minimally activate rotator cuff muscles.

This study was published in the journal of Shoulder and Elbow Surgery under the title of "Electromyographic activity in the shoulder musculature during resistance training exercises of the ipsilateral upper limb while wearing a shoulder orthosis" in June 2014.

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All the authors were involved in development of the research idea. The article was revised several times by all the co-authors and approved. The article has been peer- reviewed and all the reviewers' questions were deliberately responded.

Electromyographic activity in the shoulder musculature during resistance training exercises of the ipsilateral upper limb while wearing a shoulder orthosis

Running title: Electromyographic activity during resistance training while using shoulder orthosis

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Abstract

Objective: Resistance training is usually postponed until three months after rotator cuff surgery to prevent the damaging effects of high muscle stress on the repaired tendon. Following upper limb immobilization, non-injured muscles as well as the repaired muscles would be affected by long term inactivity. Theoretically exercises with minimal cuff activity may be appropriate in the early post-operation period, so we aimed to quantify the effect of some resistance exercises on the muscle activity of a semi-immobilized upper limb.

Method: Fifteen shoulder muscles of the dominant limb of 14 healthy subjects were evaluated using electromyography, with 11 surface electrodes and 4 fine wire electrodes in the rotator cuff muscles. Whilst wearing an orthosis the subjects completed resistance tests including: elbow and wrist flexions with three loads, maximal squeezing and shoulder adduction against three foams with different stiffness. The peak activity of each muscle was normalized to maximal voluntary contraction (% MVC) and averaged across the subjects.

Results: Shoulder muscles were activated less than 20% MVC during elbow and wrist flexions with 2 and 4 lbs loads. In the maximal squeezing test rotator cuff activity increased significantly and in some cases exceeded 20% MVC. With all three foams during shoulder adduction tests, subscapularis, latissimus dorsi, triceps and pectoralis major had the highest activation levels, which surpassed 20% MVC, while supraspinatus and infraspinatus were minimally activated.

Conclusion: Some resistance training exercises can minimally activate the rotator cuff muscles while potentially preventing the negative side-effects of muscle disuse on other upper limb musculature.

Keywords: electromyography, orthosis, resistance training, rotator cuff, shoulder, rehabilitation

Introduction

Recovery of shoulder strength after rotator cuff surgery is an important part of all rehabilitation protocols. For the first six weeks after surgery the shoulder is generally immobilized and exercises that generate high rotator cuff activity are usually avoided. During this time rehabilitation involves passive exercises that minimize loads across the repair.(13, 34) From six weeks postoperatively, active range of motion exercises are gradually introduced and from three months after surgery strength training usually starts with isometric exercises at first, and then resistance exercises using an elastic band.(34, 38) Hence not only the rotator cuff muscles, but all the shoulder muscles are in a largely inactive condition for at least the first three months after surgery. Considering that shoulder orthoses often also immobilize the elbow and wrist joints, the same assumption can be made for all the upper limb muscles. Studies have shown that neural activation and muscle strength can be impaired after just two to five weeks of joint immobilization,(16, 20) so strength loss can be expected for all of the upper limb muscles following six weeks of immobilization. In addition strength is diminished with disuse,(23, 29) therefore the further six weeks of low muscle activity can be expected to if not exacerbate, at least maintain the strength loss.

The main reason for postponing strength training after rotator cuff surgery is that high muscle activity can damage the repaired tendon.(36) However, if resistance training can be shown to activate the shoulder and upper limb muscles independently or with minimal activation of the rotator cuff, it can be assumed that such training may be implemented in the postoperative period without harming the repaired tendon. For instance Smith et al.(40) found that isolated scapular depression and protraction motions could maintain low levels of electromyographic activity in the supraspinatus and infraspinatus muscle while producing levels of electromyographic activity sufficient enough for strengthening serratus anterior and trapezius muscles. It was also suggested that selected kinetic chain exercises could potentially be implemented during periods of shoulder immobilization.(41) However, these studies investigated only a limited range of activities and therefore further research of the effect of resistance training exercises on the immobilized shoulder musculature is required. Alenabi et al.(1) found that unresisted elbow, wrist and finger movements minimally activated the rotator cuff muscles and therefore could be considered potentially safe during the post-operative period. Thus it is of interest to determine if these same activities could be safely performed with resistance.

The purpose of this study was to identify resistance training exercises of the ipsilateral upper limb that could be safely performed during post-operative immobilization. Furthermore, we intended to quantify the effect of different loads on shoulder muscle activity. We hypothesized that some resistance training exercises will minimally activate the rotator cuff muscles whilst effectively activating other upper limb musculature.

Methods

The dominant shoulders of fourteen healthy volunteers (10 men, 4 women; 12 right handed, 2 left handed; mean age, 25 ± 4 years; mean weight, 73.4 ± 9.5 kg; mean height,1.74 ± 0.08 m) were evaluated using electromyography (EMG). All subjects were free from shoulder and neck pain or disability as determined by DASH questionnaire,[22] and exhibited full pain free shoulder range of motion. The study was approved by the university research ethics committee (Comité d'éthique de la recherche en santé, certificate number CÉRSS # 2010-1013-P) and the subjects signed a consent form before involvement in the study.

Rectangular silver-silver chloride bipolar surface electrodes (20 mm inter-electrode distance, CareFusion, USA) and standard placement techniques,[6, 8, 12, 39] were used to record EMG signals from shoulder muscles of the dominant limb, including the anterior, middle and posterior deltoid, upper, lower and middle trapezius, biceps, triceps, latissimus dorsi, pectoralis major (sternal), and serratus anterior. Fine-wire intra muscular electrodes (30 mm, 27 gauge, CareFusion, USA) were used to record EMG signals from the rotator cuff. Specifically the electrodes were inserted into the supraspinatus, infraspinatus and teres minor as described by Perotto & Delagi [37] and into the lower subscapularis as described by Kadaba et al.[25] using standard aseptic techniques. The ground electrode was placed on non-dominant clavicle. To check electrode placement, the subjects were asked to perform sub-maximal isometric contractions in specific positions that were expected to generate high EMG activity and the EMG signals were evaluated. Finally the subjects performed maximal voluntary contraction (MVC) tests following the protocol outlined in our previous study [1] to determine the MVC for each of the 15 muscles.

Immobilization

The dominant shoulder was immobilized using two orthoses, both of which elevated the arm in the scapular plane.

- Type 1 (Figure 1): This custom orthosis (Laboratire Orthopédique Médicus, Montréal, Canada) was a pre-production prototype and has not yet been tested on a patient population. The orthosis was fixed to the waist using a belt, and supported the forearm between the elbow and wrist. The length of the support bar between the elbow and the waist could be adjusted so as to abduct the shoulder whilst supporting the forearm. The subject could flex and extend their elbow in the horizontal plane, flex, extend and rotate their wrist, and move their fingers while wearing the orthosis.
- Type 2 (Figure 2a): This standard orthosis (Otto Bock HealthCare GmbH, Duderstadt, Germany) was fixed to the waist and the contralateral shoulder using two belts. The ipsilateral shoulder was immobilized in abduction using a removable wedge, whilst the elbow and wrist were also immobilized. During the tests the rigid wedge was replaced by wedge shaped foams of three different densities keeping the shoulder in 42° of abduction (Figure 2b). Appendix 1 explains how the foam densities were compared and highlights the differences between the foams.

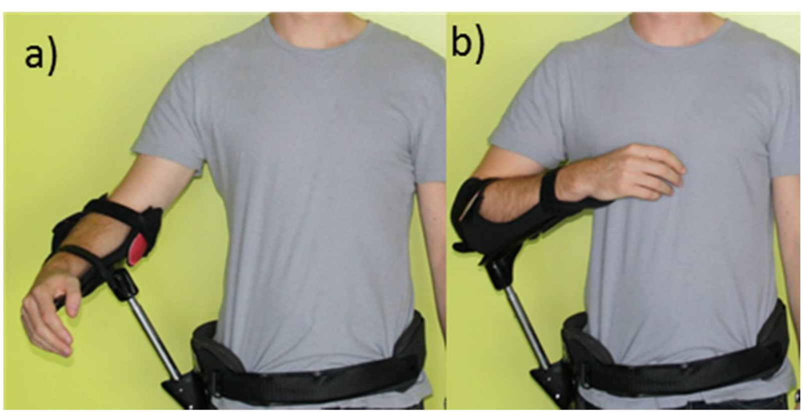

Figure 1: Orthosis Type 1, showing the allowed elbow movement; a) extended, b) flexed.

Figure 2: a) Orthosis Type 2, b) Arm adduction exercises using foams.

Tests

While wearing the shoulder orthosis, the subjects completed a number of tests using the ipsilateral upper limb. The tests are explained in detail in Table 1. There was one minute rest between tests. Where applicable a metronome was used to control the pace of the movements.

Table 1: The movements performed using the ipsilateral upper limb

Movement	Start position	Test details	Load	Rhythm
Elbow Flexion/Extension	Standing, elbow extended	10 cycles of elbow extension-flexion in the horizontal plane with each load	2, 4 and 6 lbs weights	40 beats /min Each cycle = 2 beats
Wrist Flexion/Extension	Standing, elbow extended	10 cycles of wrist extension-flexion with each load	2, 4 and 6 lbs weights	40 beats /min Each cycle = 2 beats
Squeezing	Standing, elbow extended	Two sets of squeezing a small anti-stress ball with maximum force for 5 sec.	Max force	30 s rest between two sets
Arm adduction	Standing, Arm in 42° Abduction	10 cycles of sub-maximally squeezing the foam which is positioned under the arm	3 foam densities	40 beats /min Each cycle = 2 beats

Data processing

A custom data acquisition program (Matlab R2012b, The Mathworks, Natick, MA) was used to collect and process the EMG data(1) to obtain the % MVC for each muscle during each movement. The electrode signals acquired at 4000 Hz were passed through an amplifier (Model 15A54, Grass Technology, West Warick, RI) with 10-1000 Hz bandwidth detection for the surface electrodes, and 10-3000 Hz bandwidth detection for the fine-wire electrodes (Common Mode Rejection Ratio > 90 dB; Input impedance>20 MΩ; Noise:10 μV peak to peak). The signals were filtered using a 2nd order Butterworth band pass filter at 20-400 Hz. A 10th order notch filter at 60, 120 and 240 Hz was also applied to remove the effect of power hum. The sliding root-mean square amplitude with a 100 ms window was calculated and normalized to generate a % MVC for each muscle. Less than 5% of the raw data was removed and not used in further analysis due to noise contamination.

For the tests with cyclic repetitions the peak activation during the six middle cycles was determined, and averaged for each participant. To determine the muscle activity patterns the means and standard deviations of the normalized EMGs were calculated across the study population and demonstrated in graphs. For the tests completed with three different loads (dumbbells or foams), a repeated measure ANOVA with repeated factors of muscle and load was performed. By considering a significant interaction between muscle and loads, we used ANOVA with one repeated factor (load) for each muscle followed by paired comparisons with Bonferroni adjustment. The value of $p \leq 0.05$ was used to determine significance. Software SPSS 20 was used for all the statistical procedures.

Many studies have used the classification of the magnitude of normalized EMG as low (< 20% MVC), moderate (21 – 40% MVC), high (41 – 60% MVC) and very high (> 60% MVC) to describe the level of muscle activities during rehabilitation exercises or sports.(7, 17, 27, 40) This classification has been also considered in this study. Low muscles activity has been reported during the first phase of early post-op rehabilitation protocol and this level of activity can be considered safe after rotator cuff surgery.(11, 19, 33) While >20% MVC activation has been considered as the activity level which is effective for moderate muscle strengthening.(27)

RESULTS

Elbow and wrist exercises

The mean peak activations of all tested shoulder muscles were less than 20% MVC during elbow extension/flexion in the horizontal plane with 2 and 4 lbs loads (Figure 3a). The mean peak activation of the biceps exceeded 20% MVC when using the 6 lbs load (24.2 ± 14.9% MVC), while the mean peak activations of other shoulder muscles remained under 20% MVC. However, when using the 6 lbs weight, in three of the fourteen cases the recorded activation of the teres minor, infraspinatus and supraspinatus surpassed 20% MVC. The effect of load on increasing the muscle activation was significant for middle trapezius, biceps, triceps, pectoralis major, and infraspinatus ($p<0.05$) as illustrated in Table 2.

The mean peak activations of the shoulder muscles during wrist flexion with the three different loads were less than 20% MVC (Figure 3b). The highest mean activation was recorded for teres minor while using the 6 lbs load (14.0 ± 10.9% MVC). Activation of the supraspinatus and subscapularis remained below 20% MVC for all subjects regardless of the load, whilst for four of the fourteen subjects, teres minor and/or infraspinatus activation surpassed 20% MVC when using the 6 lbs load. The effect of load on increasing the muscle activity was significant for lower trapezius, middle deltoid, biceps, pectoralis major and serratus anterior, $p<0 .05$ (Table 2).

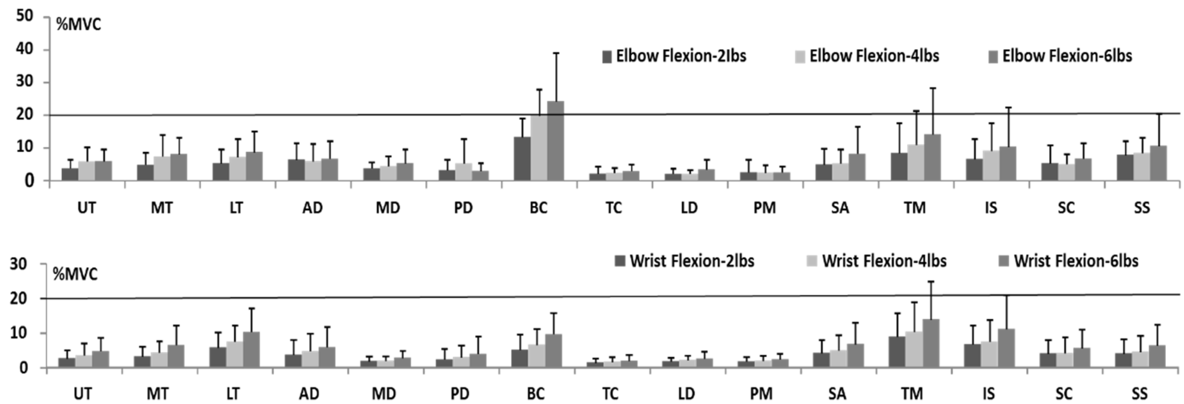

Figure 3: Shoulder muscle activity whilst wearing an orthosis during: a) elbow flexions using 2, 4 and 6 lbs loads; b) wrist flexions using 2, 4 and 6 lbs loads.

UT=Upper Trapezius; MT=Middle Trapezius; LT=Lower Trapezius; AD=Anterior Deltoid; MD=Middle Deltoid; PD=Posterior Deltoid; BC=Biceps; TC=Triceps; LD=Latissimus Dorsi; PM=Pectoralis Major; SA=Serratus Anterior; TM=Teres Minor; IS=Infraspinatus; SC=Subscapularis; SS=Supraspinatus, 2 lbs = 907 grams, 4 lbs = 1814 grams and 6 lbs = 2722 grams.

Table 2: Comparison of muscle activation between loads

Elbow Flexion with 2, 4 and 6 lbs loads

Load	UT	MT	LT	AD	MD	PD	BC	TC	LD	PM	SA	TM	IS	SC	SS
2-4	-	-	-	-	-	-	*	-	-	-	-	-	*	-	-
2-6	-	*	-	-	-	-	*	*	-	*	-	-	-	-	-
4-6	-	-	-	-	-	-	-	*	-	-	-	-	-	-	-

Wrist Flexion with 2, 4 and 6 lbs loads

2-4	-	-	*	-	-	-	*	-	-	*	-	-	-	-	-
2-6	-	-	*	-	*	-	*	-	-	-	*	-	-	-	-
4-6	-	-	-	-	*	-	*	-	-	-	*	-	-	-	-

p=<.05, the difference is significant

UT=Upper Trapezius; MT=Middle Trapezius; LT=Lower Trapezius; AD=Anterior Deltoid; MD=Middle Deltoid; PD=Posterior Deltoid; BC=Biceps; TC=Triceps; LD=Latissimus Dorsi; PM=Pectoralis Major; SA=Serratus Anterior; TM=Teres Minor; IS=Infraspinatus; SC=Subscapularis; SS=Supraspinatus

Maximal squeezing

When the subjects maximally squeezed an anti-stress ball, rotator cuff activity increased significantly and in six of the fourteen cases exceeded 20% MVC, but the mean peak activations were below 20% MVC (17.7 ± 12.2% MVC for teres minor, 15.0 ± 13.4% MVC for infraspinatus, 15.8 ± 11.1% MVC for subscapularis and 12.7 ± 8.8% MVC for supraspinatus) (Figure 4). Biceps and triceps showed the highest activation levels with 42.2 ± 20.1% MVC and 41.8 ± 31.0% MVC respectively, whilst the mean peak activation of latissimus dorsi and lower trapezius also surpassed 20% MVC. There was high variation in muscle activation between the study subjects.

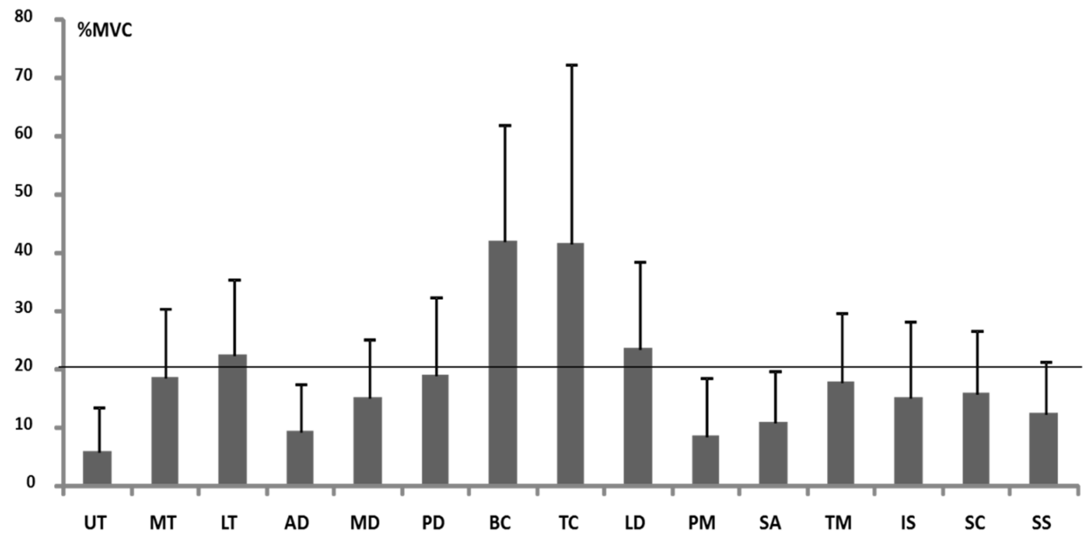

Figure 4: Shoulder muscle activity whilst wearing an orthosis during maximal squeezing.

UT=Upper Trapezius; MT=Middle Trapezius; LT=Lower Trapezius; AD=Anterior Deltoid; MD=Middle Deltoid; PD=Posterior Deltoid; BC=Biceps; TC=Triceps; LD=Latissimus Dorsi; PM=Pectoralis Major; SA=Serratus Anterior; TM=Teres Minor; IS=Infraspinatus; SC=Subscapularis; SS=Supraspinatus

Arm adduction exercises

For this test the subjects sub-maximally squeezed the foam wedges of three different densities which were positioned under arm. With all three foams latissimus dorsi, triceps, pectoralis major and subscapularis had the highest activation levels, which surpassed 20% MVC (Figure 5). In contrast supraspinatus and infraspinatus were minimally activated, with mean peak activations below 20% MVC. Statistical analysis showed significant differences in the levels of muscle activity between foams for middle trapezius, biceps, triceps, latissimus dorsi, pectoralis major, serratus anterior, teres minor and subscapularis ($p<0.05$) (Table 3).

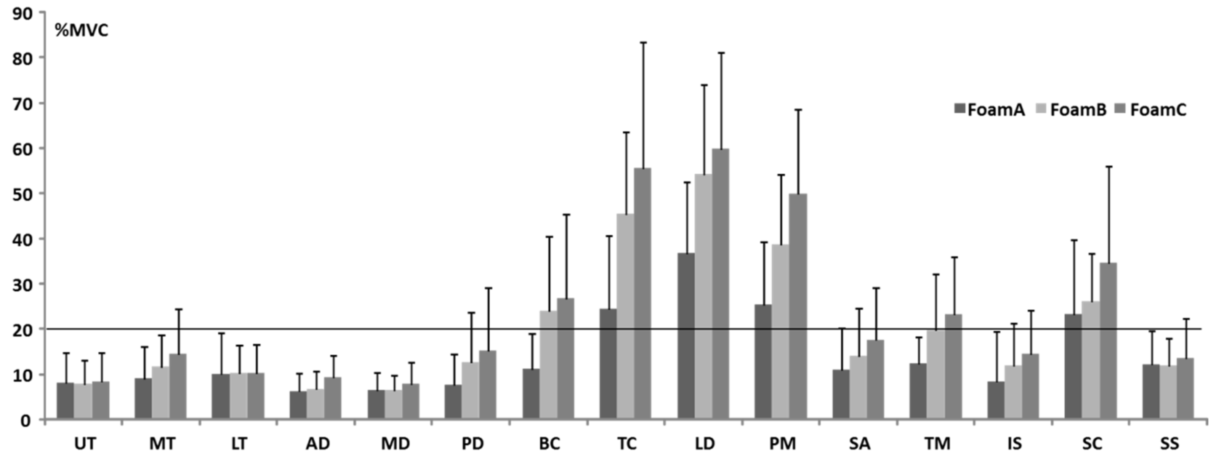

Figure 5: Shoulder muscle activity whilst wearing an orthosis during arm adduction exercises with three different foams.

Table 3: Comparison of muscle activation between foams

Foams	UT	MT	LT	AD	MD	PD	BC	TC	LD	PM	SA	TM	IS	SC	SS
A-B	-	*	-	-	-	-	*	*	*	*	-	-	-	*	-
A-C	-	*	-	-	-	-	-	*	*	*	*	*	-	-	-
B-C	-	-	-	-	-	-	-	-	-	*	-	-	-	-	-

p=<.05, the difference is significant

UT=Upper Trapezius; MT=Middle Trapezius; LT=Lower Trapezius; AD=Anterior Deltoid; MD=Middle Deltoid; PD=Posterior Deltoid; BC=Biceps; TC=Triceps; LD=Latissimus Dorsi; PM=Pectoralis Major; SA=Serratus Anterior; TM=Teres Minor; IS=Infraspinatus; SC=Subscapularis; SS=Supraspinatus

DISCUSSION

The purpose of this study was to identify resistance training exercises that could be performed during post-operative immobilization without inducing high activation of the rotator cuff muscles. Preserving muscle strength after rotator cuff surgery is important for recovery of normal shoulder function and prevention of recurrent defect.[15] Furthermore, for certain populations such as athletes or manual laborers, this is even more important. It can be assumed that after six weeks of immobilization, not only the shoulder muscles but also all the upper limb muscles would have experienced significant strength loss.[20, 31] Moreover, it has been shown that six weeks of immobilization also resulted in humeral bone density loss and good bone recovery is thought to be related to recovery of normal shoulder function.[32] Therefore it is of interest to identify resistance training exercises that can be performed safely in post-operation period in order to maintain upper limb muscle strength or at least reduce the amount of strength lost. In this study, the safety margin was set with low EMG activity (< 20% MVC) for the repaired muscles. The results of this study indicate that some types of resistance training exercises of upper limb muscles could minimally activate the rotator cuff and may be applicable during the post-operative immobilization period.

During elbow flexion/extension exercises with 2 and 4 lbs weights activation of the rotator cuff muscles remained below 20% MVC, whist the biceps was more highly activated. Increasing the load resulted in a significant increase in EMG activity of some shoulder muscles (Table 2), a finding which is similar to previous studies,[2, 3] but aside from the infraspinatus, the activation of the rotator cuff muscles did not change considerably with increased load. Elbow flexion with a 6 lbs load activated the biceps more than the lighter loads but the activity level of rotator cuff muscles also surpassed 20% MVC in some cases. Therefore resistance training with 2 and 4lbs loads can be considered potentially safe, whilst a 6 lbs load may endanger the repaired tendon. The higher load is also better to be avoided when there is concomitant biceps pathology[46] or when a biceps tenotomy/tenodesis has been performed at the time of rotator cuff repair.[21] Laursen et al.[28] have shown that shoulder muscle activity increased by increasing the speed of a hand movement task. Our previous study[1] has also shown that unresisted elbow flexion with higher speed could result in higher muscle activation specially in biceps. In the present study the elbow movement was slow (40 beats/min), so it should be noted that increasing speed can change the level of muscle activity.

Wrist exercises with the three different loads did not highly activate the rotator cuff muscles. The results showed that teres minor had the highest activity among the muscles of this study which can be attributed to its stabilizer role.[5] Wrist flexion with 6 lbs load activated the infraspinatus and teres minor more than 20% MVC in four of fourteen cases. Our results suggest that wrist resistance training with loads of up to 6 lbs can be expected to minimally activate the rotator cuff muscles. However, when a patient has an injury of the teres minor or infraspinatus, wrist resistance exercises with 6 lbs load may need more caution. It seems that rotator cuff muscle activity increased due to a demand for co-contraction to stabilize the shoulder joint and allow for better wrist control.

Maximal squeezing highly activated the biceps and triceps (> 40% MVC) and moderately activated the lower trapezius and latissimus dorsi (> 20% MVC), whilst the mean peak activations of the rotator cuff muscles remained low (< 20% MVC). However there was a large variability of rotator cuff activity between subjects. In this study we did not evaluate the levels of muscle activity during sub-maximal squeezing or repetitive squeezing exercises. But there are studies[42, 43] that showed both static and dynamic hand gripping tasks at 30% and 50% MVC, particularly in elevated arm positions, increased the load on some shoulder muscles including the rotator cuff muscles. It was also suggested that gripping redistributes muscle activity from the deltoid muscle group to the rotator cuff.[3] So it is wise to say that maximal squeezing which is similar to a gripping task may not be a safe activity after rotator cuff repair. Furthermore muscle activity can be influenced by the manner in which a mechanical load is controlled.[9] In our test maximal squeezing was completed whilst standing with the elbow extended. Changing the upper extremity posture may affect muscle activity such as it affects grip strength.[4, 26]

In this study we did not evaluate the activity of forearm muscles, but it can be expected that 6 weeks immobilization of the upper limb with a standard orthosis, that immobilizes not only the shoulder but also the elbow and wrist, would result in strength loss of the forearm muscles as well as of the arm muscles. MacDougall et al.[30] have shown that six weeks immobilization of the elbow resulted in a 41% strength loss and significant decrease in fast twitch and slow twitch fibers areas in triceps bracheii. Resistance training of the elbow and wrist joints could prevent the strength loss of forearm muscles. Davies et al.[10] showed that six weeks of isometric strength training increased the size and strength of elbow flexor muscles. Moss et al.[35] also showed that dynamic training with loads of 15% and 35% of 1RM (1 Repetition Maximal) resulted in an increase in 1RM of elbow flexors. We suggest that resistance training exercises that mobilize the elbow and wrist joints whilst minimally activating the rotator cuff muscles may be appropriate during the first phase of rehabilitation, and may prevent the complications of muscle disuse.

In our previous study[1] we found that certain elbow, wrist and fingers movements could be considered potentially safe during the post-operation immobilization period, and suggested semi-immobilization instead of full-immobilization of the upper limb after rotator cuff repair. In the present study we studied adduction movement of the shoulder against three types of resistance, to add the idea of shoulder semi-immobilization. Adduction exercises with a low density foam minimally activated the supraspinatus, infraspinatus and teres minor while moderately activating the subscapularis, pectoralis major, latissimus dorsi and triceps muscles. The muscle activation significantly increased with increasing foam density for 8 of the 15 muscles studied (Table 3). For some subjects adduction exercises with a high density foam resulted in activation of above 20 % MVC for all four rotator cuff muscles, although the mean peak activation levels were still below 20% MVC for supraspinatus and infraspinatus. In general we can conclude that low density foam resulted in the safest activity pattern. For tears in which the subscapularis and biceps are not involved, adduction resistance training with low density foam maintains minimal activation of the injured muscles. However, it is not clear if decreasing the degree of shoulder abduction (which occurs as the subject squeezes the foam) could have any harmful effect on repaired tendon. It has been shown that the optimal position of shoulder immobilization will depend on the injury, but generally that abduction of around 60° is required.[24] During the adduction exercise, the shoulder position repeatedly changed from approximately 42° to approximately 20° of shoulder abduction. Whether this range of shoulder abduction is enough to protect the repair requires further investigation.

It is known that an increase in the firing rates of motor units increases force and the integrated form of EMG, and there is at least a qualitative relation between the EMG signal and muscle force.(45) However, the authors acknowledge that EMG cannot quantitatively measure the amount of tension on the repaired tendon. It was suggested that a suitably calibrated EMG can be used as a coarse predictor of muscle tension for muscles whose length is not changing rapidly.(47) Our subjects' shoulders were in an immobilized or semi-immobilized position, and we observed that light resistance exercises of shoulder, elbow and wrist joints could minimally activate the rotator cuff muscles which is compatible with the first phase of rehabilitation protocols, so we could speculate that these types of training may not impose a high force on the repaired tendon and can be 'potentially' safe.

We appreciate that there may be differences between healthy volunteers and individuals with known shoulder pathology. However, we chose to complete this study using healthy volunteers as a first step towards optimizing post-operative immobilization protocols. Secondly much of the scientific information regarding shoulder rehabilitation has been yielded from the evaluation of young healthy subjects.(11, 19, 33, 44) Thirdly, EMG data is commonly normalized based on MVC levels and such types of contraction are not only unsafe to assess on individuals with known shoulder pathology, but also are generally not accurate as muscle pain can reduce MVC level(18) and change EMG activity.(14) The authors appreciate that further testing on a patient population is required.

CONCLUSION

Some resistance training exercises do not require high activity of the rotator cuff muscles and therefore can be considered potentially safe in the post-operation immobilization period. Such training may help preserve muscle strength in the forearm, arm and some shoulder muscles, and prevent the negative side-effects of muscle disuse. The authors believe that the results of this study suggest that rehab protocols could be modified based on the specifics of an individual's injury, and also promote the design of shoulder orthosis that provides semi-immobilization of the upper limb.

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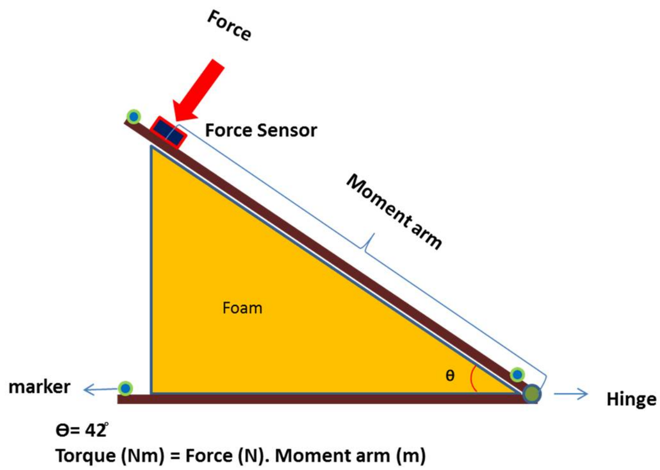
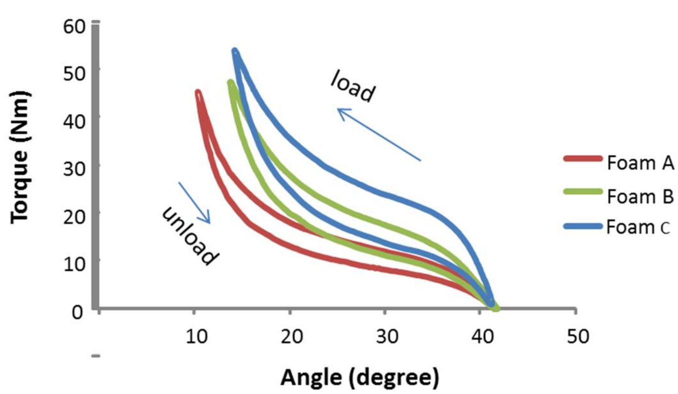
Appendix 1:

To quantify the foam characteristics a device with two hinge jointed arms as depicted below, was used. The lower horizontal arm was fixed to the floor and a force sensor was mounted to the upper movable arm. Three reflective markers were placed on the device such that angle changes could be detected using an optoelectronic system. The moment arm, which was comparable with a human's upper arm length, was constant for all foams. A force was applied perpendicular to the moveable arm. The torque (Nm) which can be determined by multiplying the force (N) by the moment arm (m) was calculated as the angle θ decreased. The graph below shows torques generated when each foam was squeezed and released.



It can be seen that the highest torque is required to compress Foam C, and that for a comparable amount of torque Foam A compresses the most. In effect, Foam C had the highest density, Foam A had the lowest density, and Foam B had a moderate density. By simulating a submaximal force which was applied during arm adduction, it can be considered that the necessary torque to change the angle from 42° to 20° degrees is 19 Nm, 30Nm and 39 Nm for Foam A , B and C respectively.



3.3 SHOULDER KINEMATIC AND EMG

This study intended to reply two following questions:

1. Does changing the plane of arm elevation affect the shoulder muscle activity pattern in patients with rotator cuff tendon tears?
2. In cuff patients, does the activity pattern of shoulder muscles change in accordance with the elevation arcs?

This article has been accepted to be published by the Journal of Clinical Biomechanics under the title of "The effects of plane and arc of elevation on electromyography of shoulder musculature in patients with rotator cuff tears". Ref no: JCLB 4080

All the authors were involved in development of the research idea. The subjects were referred from the shoulder clinic of Dr. Tétreault. Data collection, kinematic analysis and statistical processing have been performed by Fabien Dal Maso. Talia Alenabi has analysed the EMG data and interpreted the statistical findings and wrote the article. The article has been revised several times by all the co-authors.

The effects of plane and arc of elevation on electromyography of shoulder musculature in patients with rotator cuff tears

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The authors have no conflict of interest to disclose. The study was approved by the university research ethics committee (Comité d'éthique de la recherche en santé, certificate number CERSS # 2010-1013-P).

ABSTRACT

Background: Arm elevations in different planes are commonly assessed in clinics and are included in rehabilitation protocols for patients with rotator cuff pathology. The aim of this study was to quantify the effect of plane and angle of elevation on shoulder muscles activity in patients with symptomatic rotator cuff tear to be used for rehabilitation purposes.

Methods: Eight symptomatic patients with rotator cuff tears were assessed by using EMG (11 surface and 2 fine wire electrodes) synchronized with a motion analysis. The subjects completed five elevations in full can position (arm externally rotated and thumb up) in frontal, scapular and sagittal planes. Muscle activity in three elevation arcs of 20° (from 0° to 60°) was presented as the percentage of mean activity. Data were analysed by mixed linear models ($\alpha = 0.003$), and Tuckey Post-hoc comparisons for significant effects ($\alpha = 0.05$).

Findings: The effect of plane was significant for supraspinatus, middle trapezius, anterior, middle, and posterior deltoid, triceps, and pectoralis major ($p < 0.001$). Supraspinatus was more active during abduction than scaption and flexion ($p < 0.05$), and its activity did not increase significantly after 40° of elevation ($p > 0.05$). Infraspinatus had similar activity pattern in the three planes of elevation ($p > 0.003$) with increasing trend in accordance with the elevation angle.

Interpretation: In any rehabilitation protocol, if less activity of supraspinatus is desired, active arm elevation should be directed toward flexion and scaption and postponed abduction to prevent high level of activity in this muscle.

Keywords: supraspinatus; active arm elevation; full can exercise; shoulder rehabilitation; 3D glenohumeral kinematics; indwelling EMG

1 INTRODUCTION

Rotator cuff disorders are among the most frequent causes of shoulder pain,(1) and many patients with rotator cuff tears are unable to use their affected limb efficiently.(2) Contribution of rotator cuff is essential for arm elevation not only to provide glenohumeral joint stability but also as arm movers in certain ranges of motion.(3, 4) Arm elevations are routinely used for clinical evaluation of shoulder dysfunction(5) and included in most of the upper-limb rehabilitation protocols.(6, 7) There is not yet consensus on an ideal exercise program to treat patients with rotator cuff disease.(8) Hence, a detailed examination of shoulder muscles activity during different tasks including arm elevation in patients with rotator cuff tear may help clinicians to design more specific shoulder rehabilitation programs.(9)

Based on electromyographic (EMG) recordings of the shoulder musculature, several studies have proposed recommendations for shoulder rehabilitation exercises.(9, 10) For arm elevation exercises, “full can” position (arm externally rotated and thumb up) is preferred to “empty can” (arm internally rotated and thumb down)(10, 11) because internal rotation of the arm may decrease the width of subacromial space(12) and hence reproduce the symptoms.(13) Among all planes in which an arm can elevate, “scaption”, i.e. elevation in the scapular plane, has been most investigated.(14, 15) However, patients are encouraged to exercise in all planes of elevation with large range of motion.(10) While kinematics-based investigations have highlighted that planes of elevation alter rotations(16) and translations(17) of the glenohumeral joint, little is known about changes in rotator cuff activation pattern induced by different planes of elevation. EMG studies on rotator cuff muscles have described the activation pattern for each of the abduction, scaption, and flexion planes separately.(18-21) To our knowledge, only Reed et al. (22) have directly compared the shoulder muscle activity patterns in three planes of elevation and reported significant main effect of plane on the activation level of supraspinatus, middle deltoid and upper trapezius muscles. However, their experiment was based only on healthy participants, which may not represent the patients with pathologic rotator cuff. Biomechanical studies have shown that glenohumeral kinematics differs between patients with shoulder pain and healthy individuals.(23) These kinematic changes may also be accompanied with alteration in EMG activation pattern.(20, 24, 25) For example, McMahon et al. (20) reported lower EMG activity of supraspinatus in the shoulders with anterior joint instability than normal population between 30-60° of arm elevation in all the three planes of elevation. Such studies have not been performed on patients with rotator cuff tears. Therefore, the comparison of shoulder EMG in different planes and angles of elevation in cuff patients is essential to characterize muscle activation pattern following rotator cuff tear in order to better direct rehabilitation programs.

The aim of this study was to assess the effect of plane, i.e. abduction, scaption, and flexion and arc of elevation, i.e. 0-20°, 20-40°, and 40-60° of glenohumeral angles, during full can elevations on the EMG of shoulder musculature in patients with rotator cuff tears. Glenohumeral angle was selected for investigation as its movement requires more precise rotator cuff activity and the rotator cuff tear is associated with disruption of normal glenohumeral kinematics.(26) We hypothesized that plane of elevation as well as elevation angle significantly affect the EMG pattern of torn rotator cuff and should be considered in different phases of rehabilitation protocols.

2 **MATERIALS AND METHODS**

2.1 **Participants**

Eight symptomatic patients with full thickness rotator cuff tears affecting one or two tendons were chosen for this study. The patients' information is detailed in Table 1. All tears were confirmed by MRI and the patients were waiting for surgery for more than six months after their diagnosis. Any patient with coexisting musculoskeletal disorder affecting the upper limb or previous surgery was excluded from the experiment. Written informed consent was obtained from all participants before the experiment. All patients were then asked to complete quick-DASH(27) and Constant(28) questionnaires by aid of the same experimenter. The research was approved by the ethics committee of the local university (CÉRSS-2010-1013-P).

Table 1: Demographic variables and functional scores

Patients	Age	Gender	BMI	Injured side	Q-DASH	Constant	Tendon torn	Tear size	Symptomatic (year)
P1	64	M	29.7	R	64	25	SS	1-3 cm	3-5
P2	55	M	30.1	L	35	57	SS	1-3 cm	1-3
P3	41	F	26.8	R	65	26	SS	<1 cm	3-5
P4	69	F	28.4	L	75	38	SS + IS	1-3 cm	3-5
P5	68	M	30.7	L	67	50	SS	1-3 cm	3-5
P6	64	F	33.6	R	44	46	SS + IS	3-5 cm	1-3
P7	49	F	27.6	R	91	18	SS + IS	3-5 cm	1-3
P8	57	F	24	R	93	13	SS	1-3 cm	1-3
Mean	58.38		28.86		66.75	34.12			
(STD)	(9.8)		(2.87)		(20.28)	(15.97)			

M = Male, F = Female, R = Right, L = Left, SS = Supraspinatus, IS = Infraspinatus, STD = Standard Deviation

2.2 **Recordings**

EMG signals were recorded from 13 shoulder muscles of the affected limb of the patients using 2 fine-wire electrodes and 11 surface electrodes. Fine-wire intramuscular electrodes (30 mm, 27 gauge; CareFusion, San Diego, CA, USA) were inserted into the supraspinatus and infraspinatus as explained by Perotto.(29) After suitable skin preparation, circular silver–silver chloride bipolar surface electrodes (20 mm inter-electrode distance; CareFusion, San Diego, CA, USA) were placed over 11 muscles, namely the long heads of triceps and biceps, anterior, middle, and posterior deltoid, latissimus dorsi, sternal part of pectoralis major, serratus anterior and upper, middle, and lower trapezius by standard placement techniques.(30-32) The ground electrode was placed on the opposite clavicle. Proper electrode placement was confirmed by checking the signals during sub-maximum isometric contractions, which were performed in specific positions expected to generate high EMG activity.(33) The EMG signals were acquired at 1000 Hz and passed through an amplifier (model 15A54; Grass Technology, West Warick, RI, USA) with 10 to 1000 Hz bandwidth detection (common mode rejection ratio > 90 dB; input impedance > 20 MΩ; noise, 10 mV peak to peak).

For kinematic analysis, the patients were setup with 29 reflective markers on the trunk and the affected arm as described by Robert-Lachaine et al.(2015).(34) Marker trajectories were tracked using an 18-camera motion analysis system (Vicon Motion System, Oxford

Metrics Ltd., Oxford, UK) at 150 Hz. EMG and kinematic data were synchronized online using the Nexus 1.8.5 software (Vicon Motion System).

2.3 Experimental procedure

Patients were standing in an anatomic posture and maintained the trunk as stable as possible. Each movement started with the arm relaxed at the side. Patients executed three repetitions of arm elevations in different planes, shoulder rolls, shrugs, and circumductions, along with five elbow flexion- extension to locate joints centers and axes of rotation.(35) Then, they were asked to perform 5 arm elevations in frontal, scapular and sagittal planes (abduction, scaption, and flexion) at their maximum range of motion with the thumb pointing towards the ceiling (full can position). One examiner was checking the exact plane of scapula for each patient and then adjusted the other two planes accordingly. Moderate self-controlled speed was maintained throughout elevations as application of metronome was not feasible due to different maximal elevation angle for each patient. Five trials were recorded in each plane of elevation and the order of planes was randomly assigned for each patient.

2.4 Data Processing

2.4.1 Kinematic

For joint kinematic analysis, the positions of the center of rotation of the sternoclavicular, acromicoclavicular, and glenohumeral joints were personalized. This personalization was performed in accordance to the recent recommendations based on a gold standard kinematics measurements performed in our lab.(36) Secondly, to improve the accuracy of kinematic reconstruction, the displacement of the scapula was constrained to follow an ellipsoid representative of the scapula-thorax interface. The geometry of the ellipsoid was optimized to fit all the markers positioned on the scapula during functional movements. The constraint imposed in a way that at least one point of the scapula was in contact with the ellipsoid. Thirdly, a kinematic chain model and a global optimization algorithm were used to reconstruct the kinematics of each degree of freedom at each frame. This method has been already shown to be relevant to minimize the effect of soft tissue artefacts.(37) The glenohumeral angles were expressed according to the Euler angle with the sequence plane of elevation, elevation, axial rotation.(38) Maximum glenohumeral and thoracohumeral elevation angles were measured for each patient in each plane of elevation. Glenohumeral elevation angles were retrieved in each plane of elevation up to 60° in three arcs: 0-20°, 20-40°, and 40-60°. Sixty degrees was chosen as it was the average of maximum glenohumeral elevation angles reached by our patients, and corresponded to the average range of motion required during most of the daily living tasks.(39)

2.4.2 **EMG**

Raw EMG signals were filtered using a 20-400 Hz band-pass eighth-order zero-lag Butterworth filter and then a 60 Hz notch-pass filter. The root-mean square (RMS) amplitude was then calculated using a 200 ms window and the muscle activation levels were obtained as follows. For each muscle, the RMS EMG of all trials in each plane was first averaged over every single degree from 0° to 60° of glenohumeral elevation. The mean EMG amplitude was then computed over abduction, scaption, and flexion from 0° to 60° of glenohumeral elevation to obtain a reference for normalization.(40) Since pain in symptomatic patients reduces the maximal contraction levels(41) and therefore muscle maximum voluntary excitation,(42) we preferred this method of normalization over maximal voluntary contractions, which is reported to be more appropriate for indwelling EMG in shoulder studies.(40) The normalized EMG values were then averaged for 0-20°, 20-40° and 40-60° of glenohumeral elevation for available range of motion. Wherever there was not any value, it was considered as "not a number" in the computing process.

2.5 **Statistics**

A linear mixed model analysis was performed using R Core Team(43) and the lme4(44) package according to Winter's method.(45) Briefly, a rank transformation from numeric to ordinal data was first applied for elevation planes and elevation angles in order to increase the statistical power. As dependent factor, the average activation levels and as fixed effect, the interaction between planes (i.e. abduction, scaption, and flexion) and arcs of elevation (i.e. 0-20°, 20-40°, and 40-60°) were entered. The intercepts by patients were considered as the random effect. The residual plots were visualised to check any deviations from homoscedasticity or normality. The p value was obtained by likelihood ratio tests of the full model against the model without the effect in question. As 13 muscles were tested by linear mixed model, a Bonferroni correction procedure was used to cope with the problem of multiple comparisons. Thus, the level of significance was set at $p < 0.003$. When linear mixed model revealed significant effects, Tuckey Post-hoc comparisons were performed to determine differences between arcs and planes of elevation, with a significance level set at $\alpha = 0.05$. Power tests were also performed for all the analyses.

3 Results

The maximum ranges of motion in three planes of abduction, scaption, and flexion according to glenohumeral and thoracohumeral angles are presented in Table 2. As three patients could not elevate their affected arms in the range of 40-60° of glenohumeral elevation, the analysis of this arc is based on the data collected from five patients only. On average the patients reached their maximum elevations after 3.2 (1.1) s, 3.1(1.2) s and 3.4 (1.4) s for abduction, scaption, and flexion, respectively.

Table 2: Maximum glenohumeral (GH) and thoracohumeral (TH) angles of elevation reached for each patient.

Patients	Maximum GH angle (°)			Maximum TH angle (°)		
	Abduction	Scaption	Flexion	Abduction	Scaption	Flexion
P1	78	62	56	103	126	124
P2	78	70	60	107	112	103
P3	64	75	62	91	101	91
P4	97	94	94	120	120	119
P5	83	78	66	102	117	112
P6	37	46	52	86	97	95
P7	24	39	50	53	68	75
P8	24	53	52	56	81	73
Mean (STD)	60.7 (28.4)	64.6 (18.0)	61.5 (14.1)	89.6 (23.9)	102.5 (20.0)	98.9 (19.0)

STD =standard deviation

The results of the linear mixed model analysis for the *plane* and *arc of elevation* effects, and *plane* * *arc of elevation* interaction are summarized in Table 3. No significant *plane* * *arc of elevation* interaction was observed for any muscle (all $p > 0.003$, power < 80%); both main effects are described in details below.

3.1 The effect of elevation plane

Figure 1 represents the EMG activity pattern of each shoulder muscle according to the glenohumeral elevation angle during abduction, scaption, and flexion. The linear mixed model analysis revealed a significant *plane of elevation* effect on the activation pattern of 7 out of 13 muscles, namely, supraspinatus, anterior, middle, and posterior deltoids, middle trapezius, triceps, and pectoralis major (all $p < 0.001$). According to the post-hoc analysis, supraspinatus, and middle and posterior deltoids were significantly more active during abduction than scaption and flexion. Moreover, supraspinatus and middle deltoid were significantly more active during scaption than flexion. Anterior deltoid and pectoralis major were more active during flexion than abduction ($p < 0.001$). Flexion produced also a significant higher activation level than scaption for the pectoralis major ($p = 0.001$) but not for anterior deltoid ($p = 0.73$). The activation level of the middle trapezius was significantly higher during abduction than scaption. The activation level of the infraspinatus did not differ between planes of elevation ($p = 0.08$).

3.2 The effect of elevation arc

The linear mixed model analysis revealed a significant *arc of elevation* effect on the activation level of all muscles ($p < 0.001$). The post-hoc analysis revealed that the activation level of the supraspinatus, posterior deltoid, middle trapezius, and triceps increased significantly from the first to the second arc of elevation, but there were not significant differences in EMG values between the second and the third arcs of elevation for these muscles. The activation level of the pectoralis major increased significantly only between the first and the last arcs of elevation ($p < 0.05$). The activation level of the other muscles of this study showed continuous and significant increase from the first to the second and the third arcs of elevation ($p < 0.05$).

Table 3: Results of the linear mixed model analyses.

Muscles	Plane of elevation						Arc of elevation						Interaction of plane * arc of elevation		
	Linear mixed model			Post-hoc			Linear mixed model			Post-hoc			Linear mixed model		
	X^2	*p* value	power	ABD *vs.* SCAP	ABD *vs.* FLEX	SCAP *vs.* FLEX	X^2	*p* value	Power	Arc 1 *vs.* Arc 2	Arc 1 *vs.* Arc 3	Arc 2 *vs.* Arc 3	X^2	*p* value	power
Supraspinatus	**49.39**	**<0.001**	**1**	**<0.001**	**<0.001**	**<0.001**	**21.34**	**<0.001**	**0.99**	**0.001**	**0.001**	0.99	3.68	0.4	0.25
Infraspinatus	4.88	0.08	0.86				**67.4**	**<0.001**	**1**	**<0.001**	**<0.001**	**0.04**	3.52	0.4	0.24
Anterior deltoid	**19.11**	**<0.001**	**0.99**	**0.001**	**<0.001**	0.7	**64.35**	**<0.001**	**1**	**<0.001**	**<0.001**	**0.04**	5.37	0.2	0.36
Middle deltoid	**20.27**	**<0.001**	**1**	**0.04**	**<0.001**	**0.04**	**77.4**	**<0.001**	**1**	**<0.001**	**<0.001**	**0.002**	4.78	0.3	0.32
Posterior deltoid	**63.62**	**<0.001**	**1**	**<0.001**	**<0.001**	**0.02**	**56.29**	**<0.001**	**1**	**0.001**	**<0.001**	0.15	5.91	0.2	0.39
Upper trapezius	3.83	0.14	0.66				**44.007**	**<0.001**	**0.99**	**<0.001**	**<0.001**	**0.04**	10.93	0.02	0.69
Middle trapezius	**31.73**	**<0.001**	**1**	**0.01**	**<0.001**	**0.002**	**45.91**	**<0.001**	**0.99**	**<0.001**	**<0.001**	0.25	5.74	0.2	0.38
Lower trapezius	0.76	0.68	0.15				**40.18**	**<0.001**	**0.99**	**<0.001**	**<0.001**	**0.007**	1.46	0.8	0.12
Biceps	7.87	0.01	0.97				**61.98**	**<0.001**	**1**	**<0.001**	**<0.001**	**0.002**	2.05	0.7	0.15
Triceps	**42.24**	**<0.001**	**1**	**<0.001**	**<0.001**	0.128	**41.33**	**<0.001**	**0.99**	**0.005**	**<0.001**	0.14	3.06	0.5	0.21
Serratus anterior	4.09	0.13	0.74				**57.107**	**<0.001**	**1**	**<0.001**	**<0.001**	**0.003**	5.81	0.2	0.38
Pectoral major	**17.52**	**<0.001**	**0.99**	0.91	**<0.001**	**0.001**	**23.75**	**<0.001**	**0.99**	0.05	**<0.001**	0.09	3.47	0.4	0.23
Latissimus dorsi	7.81	0.02	0.99	n.a.	n.a.	n.a.	**78.106**	**<0.001**	**1**	**<0.001**	**<0.001**	**<0.001**	8.37	0.07	0.55

Note. ABD = Abduction, SCAP = Scaption, FLEX = Flexion, Arc 1 = 0-20°, Arc 2 = 20-40°, Arc 3 = 40-60°, $p < 0.003$ for mixed linear model, $p < 0.05$ for post hoc comparison, *Bold values indicate significant main effects.*

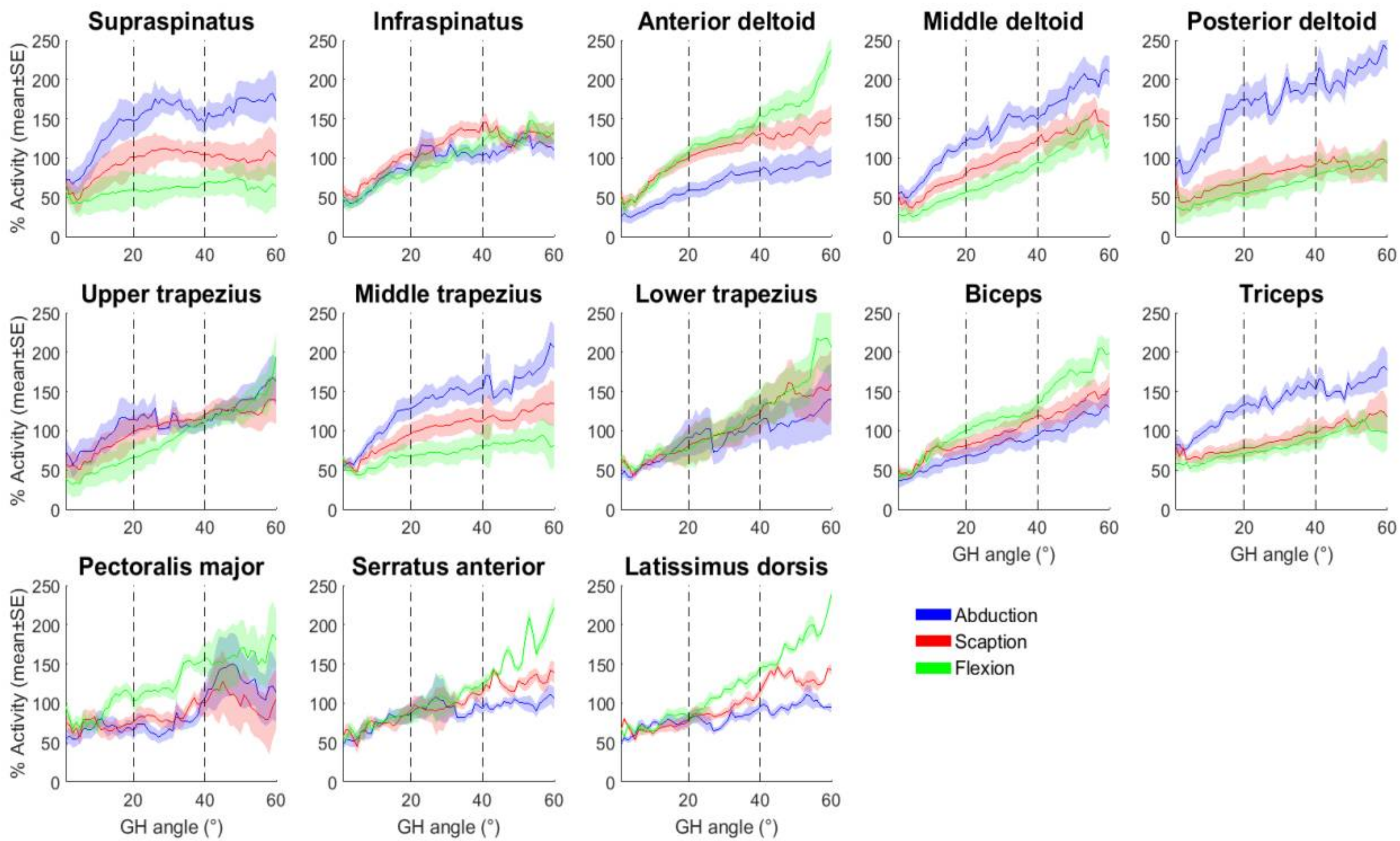

Figure 1: Average and standard error (SE) of muscle activation according to the glenohumeral elevation angle during abduction, scaption, and flexion for each muscle.

4 Discussion

The purpose of this study was to assess the effects of plane and arc of elevation on the shoulder muscle electromyography in patients with full thickness rotator cuff tears during maximum abduction, scaption, and flexion. The main findings are that in this group of patients, the activity of the supraspinatus muscle was significantly higher during abduction than scaption and flexion, while infraspinatus had similar activity pattern in the three planes of elevation. Moreover, the activity of supraspinatus did not significantly increase after 40° of glenohumeral elevation, while the activity of infraspinatus continuously increased throughout the range of elevation.

To the best of our knowledge, only Reed et al.(22) have directly compared the effect of elevation plane on shoulder muscles activities and found main significant effect only for supraspinatus, middle deltoid and upper trapezius. However, their experiment involved healthy participants with intact cuff, who might have different muscle activity pattern than the patients with cuff tear. In addition, their subjects held 50% of their maximum abduction load during arm elevation; this task may not be applicable to patients with rotator cuff tears in pre or postoperative periods due to increasing pain or risk of re-tear respectively. Although methodological differences limit the comparison, we highlighted additional statistically significant effects which emphasizes that more investigations on rotator cuff patients are needed. For supraspinatus, Reed et al.(22) did not observe any significant difference in the muscle activity between scaption, abduction, and scapular +30° planes, which is different from our findings in patients with cuff tear. Similarly, we found no effect of elevation plane on infraspinatus activity.

Rotator cuff tear is associated with disruption of normal glenohumeral kinematics,(26) that may cause higher supraspinatus activity, especially during abduction, to center the humeral head into the glenoid. It has been shown that supraspinatus has higher moment arm and greater elevation torque during abduction than scaption,(46) but this issue has not yet been verified in patients with torn tendon. Maybe supraspinatus generates more force during abduction to compensate the tendon defect. Other biomechanical study has also suggested that supraspinatus is more effective in smaller arcs because its moment arm decreases with higher elevation angles,(47) and EMG studies have confirmed higher activity level of supraspinatus in the lower arcs of motion.(14, 20) It is not clear how the moment arm can be affected by rotator cuff tear, however, unlike the aforementioned observations, the activity of supraspinatus in our patient population was steadily increasing with the elevation arcs, but this increase was not statistically significant during the last arc of elevation. It means that in patients with rotator cuff tear, the increasing trend in supraspinatus activity was more gradual after 40° of glenohumeral elevation.

Along with supraspinatus, middle deltoid as one of the main abductors (48) was significantly more active in abduction than in scaption and flexion which is in agreement with Reed et al.(22) The same pattern was also observed for the posterior deltoid and triceps. Several studies (49-51) have suggested that disruptions in the normal function of some rotator cuff muscles may place a higher demand on deltoid to elevate the arm. Our study showed that this demand is significantly higher during abduction than scaption with greater involvement of middle and posterior deltoid in patient population. Adductor muscles (pectoralis major and latissimus dorsi) as the most effective humeral head depressors,(46) are contributing in shoulder stability, considering that marked decrease in their activities has been reported in patients with anterior shoulder instability,(52) and patients with massive cuff tears showed higher activity of adductor muscles than normal subjects.(53) However, while latissimus dorsi, in our patient population had the same pattern of activation in all planes of elevation, pectoralis major was significantly more active during flexion than abduction and scaption. This finding might be attributed to the flexor activity of some parts of pectoralis major.(54)

The above findings have two main applications. Firstly, while scaption in full can position has been suggested as the optimal testing position for supraspinatus isolation,(55, 56) our results showed that arm abduction produced significantly higher supraspinatus activation than scaption. This observation suggests that the optimal muscle testing position for supraspinatus in patients with cuff tear may be abduction instead of scaption. Secondly, it is usually advised to avoid the movements that create high activity of rotator cuff muscles in the early phases of rehabilitation post rotator cuff repair.(9) The differences in shoulder muscles activation pattern in pre and post-rotator cuff repair have not been highly studied, but recently de Witte et al. (57) reported that the compensatory increased deltoid activation in patients with cuff tear has partially reduced one year after surgical repair. However, the differences in activation ratio in pre and post repair were small and statistically non-significant. Therefore, it can be assumed that patient’s muscle activity pattern might not dramatically change in the early post-op phases. Conclusively, in any rehabilitation approach, if less activation of supraspinatus is desired, we suggest that active elevation exercises being started in flexion plane with gradual progress to scaption and abduction. In addition, after a certain level of arm elevation (40° of glenohumeral angle), the activity of supraspinatus might not significantly differ while for infraspinatus, increasing the elevation arcs causes higher activation of the muscle. Therefore, based on the affected tendon/s, the plane and angle of elevation can be adjusted. We acknowledge that muscle activity is not the only indicator of stress on repaired tendon. However, as there is at least a qualitative relationship between muscle force and muscle activity (9), it can be assumed that when muscle is more active, it may generate more force that may increase the possibility of stressing the repaired tendon. Indeed, rehabilitation studies are looking for this possibility and this concept has been the basis of many rehabilitation regimens.

In the present study, a personalized kinematic model (34, 58) was used to obtain accurate shoulder kinematics data. Patients with rotator cuff pathology usually use different compensatory mechanisms for arm elevation such as increasing posterior scapular tilt(59) or greater scapular elevation,(60) that may change the orientation of their glenohumeral joints.(34) Therefore, two patients with the same maximal thoracohumeral arm elevation may have different glenohumeral contribution. For example, Patient 3 and 6 only had 5° differences in maximum thoracohumeral abduction, but 27° in glenohumeral elevation. The latter difference means that Patient 6 was using more compensatory mechanisms for arm elevation. This may be attributed to the larger tear size in Patient 6, however, there is evidence suggesting that the severity of symptoms does not correlate with the severity of rotator cuff disease.(61) For instance, Patient 7 and Patient 8, despite having different tear characteristics, similarly had very limited maximal arm elevation. Conventional methods for measuring elevation angles such as goniometer or 2D kinematics, usually measure thoracohumeral angles without considering the glenohumeral contribution. As rotator cuff mainly acts on glenohumeral joint, for the kinematic studies that rotator cuff is of interest, a 3D motion analysis may be a better choice to dynamically calculate the glenohumeral contribution during arm elevation. Although this method has limited clinical applicability, it is more reliable in patients with altered shoulder kinematics and is more useful for further comparisons. However, to facilitate the clinical usage, the maximal thoracohumeral elevation angles have also been reported in this study.

The main limitation of this study was the small sample size. To overcome this limitation, we used a statistical analysis adapted to small samples (45) and we obtained high powers for all the significant effects. However, considering the low power of some non-significant findings such as the interaction effect of planes and arcs of elevation, those results should be interpreted with caution. It should be noticed that pre-repair situation may not represent the post-repair condition, however, due to high risk of re-tear after surgery, such experiments in early post-op period may not be feasible. We did not also compare the shoulder muscle activity of the patients with normal population, because the main question of this study was the muscle activity pattern in patients with rotator cuff tears, no matter what the normal pattern is. We acknowledge that the different protocol used by Reed et al. (22) would also limit this comparison.

5 Conclusion

Both the plane and the arc of arm elevation affect shoulder muscle activity in patients with rotator cuff tears. The supraspinatus with torn tendon was significantly more active during abduction than scaption and flexion. We suggest that in any rehabilitation protocol if less activity of supraspinatus is desired, active arm elevation should be directed toward flexion and scaption rather than abduction. The plane of elevation does not change the activity pattern of infraspinatus but its activity increases significantly in accordance with the elevation angles. Therefore, according to the affected tendon/s and the rehabilitation goals, the plane and angle of elevation can be adjusted. The results of this study may help clinicians to choose more precisely the rehabilitation movements for their patients.

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4 GENERAL DISCUSSION

The main objective of this thesis was to evaluate the EMG activity of shoulder musculature during different exercises and tasks that are theoretically suitable for the early rehabilitation phases after rotator cuff repair. The specific objective of this thesis was to introduce a semi-immobilization concept for the period of early rehabilitation after rotator cuff surgery and suggest some exercises that can be safely performed during that period. Success in surgical treatment of rotator cuff tear is highly dependent on a good post-surgical rehabilitation protocol beside the good surgical technique. All rehabilitation regimens aim to implement a series of exercises that restore optimal function, while protecting the anatomic integrity of the injured or repaired tissues. Based on animal studies, the process of tendon healing may take 12-16 weeks.[232] Therefore, the first 3 months after rotator cuff repair is a critical time period for completing the healing process. The progression of exercise intensity is within the healing tissue's capabilities. In this respect, more conservative approach is warranted for this time period, and heavier exercises are postponed to few months after surgery when the healing tissue has enough strength to deal with external forces.

Four to five phases of rehabilitation after rotator cuff surgery have been introduced.[233,234] Protection of the repaired tissue is the focus of the initial phase of rehabilitation. In this phase, the primary post-surgical goal is to minimize stiffness and muscle atrophy while allowing healing of the repaired tendon. The integrity of the repaired tissues is preserved by immobilizing the operated shoulder to impose as less stress as possible on the newly repaired tissues. The first objective of this dissertation was to challenge the immobilization method and introduce a semi-immobilization concept. We intended to show that immobilization could be limited to shoulder joint and mobility of the other parts of upper limb might not highly activate the cuff muscles. Usually during immobilization period, passive range of motion exercises are prescribed to minimize stiffness and muscle atrophy. The other objective of this dissertation was to introduce some exercises and daily living tasks that do not highly activate the rotator cuff muscles and could be added to the rehabilitation regimen. Our first article evaluated these two objectives.

At the end of the first phase of rehabilitation or in the beginning of the second phase, when a desirable passive ROM is achieved, patient is ready to start active assisted or active movements. Active movement can apply certain forces that aid in orienting the fibers within the collagen matrix and enhancing the tensile strength of the repair.[125] We intended to evaluate the sequences of active arm elevation exercises in respect to plane and arc of elevation. We wanted to show how changes in plane or arc of elevation can affect the EMG pattern of shoulder musculature. This issue was evaluated by using the kinematic analysis in accompanying with EMG and presented in our third article.

When the patients demonstrate adequate passive and active glenohumeral range of motion, strengthening of rotator cuff muscles begins. Rotator cuff strengthening are usually prescribed after 3 months of operation, but all the other resistance trainings are also postponed until this phase of rehabilitation. The other objective of this thesis was to evaluate the activity of rotator cuff muscles during some light strength training exercises, assuming that these exercises could be started earlier during the immobilization period without creating high force within the cuff muscles. These strength training exercises should ideally target the other upper limb muscles rather than rotator cuff and may prevent muscle atrophy and strength lose. This idea has been discussed in our second article.

Phase four and five of rehabilitation consist some advanced strengthening exercises and restoration of functional activities which are beyond the scope of this thesis.

As it was deliberated before, the rehabilitation protocols are progressing from a maximum protection phase to a minimum protection phase. To translate the above concept in an EMG language, it can be said that based on activation of rotator cuff muscles, the patient experiences a gradual progression of rotator cuff loading within each phase. Exercises resulting in minimal EMG activity of rotator cuff muscles begin in the earlier phases when repair integrity and avoidance of imposing stress on the repair is critical; whereas strengthening exercises that create higher EMG activity in rotator cuff muscles begin in the later phases.[235] It is supposed that this gradual progression of increasing EMG activity facilitates protection of the repaired tissue during the first phases of healing. This concept has been followed in the studies presented in this dissertation.

Although the understanding of healing process and muscle activity behavior has guided many rehabilitation regimens, in real world, rehabilitation protocols vary widely with respect to timing of progression and appropriate exercises. This diversity is because most rehabilitation protocols are based on clinical experiences and experts' opinions, rather than scientific evidence. This issue is even more significant for the early phases of rehabilitation post rotator cuff repair. Indeed, current literature is mostly concentrated on subacute recovery phases in which resistive exercises are incorporated and limited research is available to provide guidance in the early phases of rehabilitation (see Table 5, section 2.4.5). In this respect, this thesis has targeted an area that still needs a lot of work. We introduced some exercises and activities that caused low activation of rotator cuff muscles while the repair site was almost protected by shoulder immobilization. Theoretically, these activities can be added to the first two phases of post-surgical rehabilitation protocols. These findings can also provide a basis for manufacturing more dynamic and functional shoulder orthoses. In the next sub-sections the main findings of our studies are discussed.

4.1 In the first phase of rehabilitation, immobilization can be limited to shoulder joint.

Almost all rehabilitation protocols agree with a period of shoulder immobilization following rotator cuff repair. This agreement is mostly based on animal studies that indicate postoperative immobilization can minimize the tension on rotator cuff repairs and may lead to improved collagen orientation and visco-elastic properties, (see Table 1, part B). In addition, excessive early activity raises concern for re-tearing or detachment of the rotator cuff repair. Despite general acceptance of shoulder immobilization for repair protection, there is still controversy regarding the optimal duration of immobilization, optimal positioning and the extent of upper limb immobilization. The latter issue was investigated for the first time in our study which was presented in article 1. Actually in both methods of shoulder immobilization, either by an arm sling or by an abduction orthosis, the elbow and wrist joints are also immobilized. Immobilization period varies between 4 to 8 weeks and according to the patient's situation, the rehabilitation protocol is selected and customized. Passive ROM exercises for shoulder joint may be started the day after operation (moderate protocol) or 2 to 4 weeks after operation (conservative protocol),[233] to prevent joint adhesions and stiffness. During the immobilization period, patients are encouraged to follow a home exercise program that consists active ROM of neck, elbow and wrist,[233] however, restriction of elbow and wrist movements while wearing orthosis, limits the functionality of patient's upper limb. Yue et al. (1997) [22] showed that 4 week immobilization of elbow joint could significantly reduce the cross-sectional area of the elbow flexor muscles and decrease their MVC forces. Immobilization of elbow and wrist joints is a traditional method which has not been supported by scientific evidence. Our results showed that the rotator cuff activity level is always below 20% MVC during elbow movements and always below 10% MVC with wrist movements. Most studies concerning the first phase of rehabilitation protocols reported that rotator cuff muscle activity of less than 20% of maximal isometric or dynamic voluntary contractions can be considered safe. For example, McCann et al. (1993) [7] studied EMG activity of shoulder muscles during the three phases of shoulder rehabilitation and considered <20% of maximal dynamic contraction as the minimum applicable activity in the first phase. Dockery et al. (1998) [236] studied different types of passive exercises commonly used in post-op period and showed that all passive exercises could activate supraspinatus muscle for less than 20% MVC, however, the level of muscle activity using pulley system was higher than CPM or self-assisted bar raise. Hintermeister et al. (1998) [219] studied EMG activity during shoulder rehabilitation exercises with elastic resistance and considered <20% MVC as the minimal muscle activity which can be considered safe in post-op period. Smith et al. (2006) [13] while studying shoulder muscle activity in immobilized shoulder during scapulothoracic exercises, have continued to advocate early low-level (<20% MVC) reactivation of the scapular stabilizers during shoulder rehabilitation. Finally, Uhl et al. (2010)[230] suggested that many exercises used during the early phase of rehabilitation to regain active elevation do not exceed 20% MVC. In this thesis we intended to show that movement of elbow, wrist and fingers could not activate the shoulder muscles higher than what is assumed to be safe in the first phase of rehabilitation protocols. It should be reminded that our subjects' shoulders were immobilized and no external forces were imposed on the shoulder muscles during the tests. We also noticed that by increasing the speed of movements, the activity of rotator cuff muscles would increase. This observation is in accordance with previous findings that showed increasing in load and speed could increase muscle activity.[237] Therefore, theoretically slow movement of elbow and wrist can be assumed safe in the first phase of rehabilitation period. This issue can be considered in designing dynamic shoulder orthoses in order to provide more comfort for patients during immobilization period. In this design, the immobilization is limited to the shoulder joint and elbow and wrist joints can be mobilized. Fortunately at the time of writing this thesis, such orthosis has been produced and introduced for clinical application.

4.2 Some daily living tasks that involve elbow, wrist and fingers can be performed in the first phase of rehabilitation.

Although there are some reports of shoulder muscles EMG during rehabilitation exercises, such studies on activities of daily living (ADLs) are scarce. When applying a rehabilitation protocol, it is important to begin by matching the patient's needs with his or her movement limitations and goals. Patients are usually interested in returning to activities of daily living as soon as possible after surgery. Although patients are asked to limit active use of the operative extremity immediately after surgery, they may still perform light activities, believing that their shoulder is protected in the sling or orthosis. Clinicians are sometimes being asked about the restrictions and activity level during immobilization period. Patients may ask if they are allowed to work with their computers or carry a light weight or write a note, etc. Little is known about muscle activation in the rotator cuff muscles when simple ADLs are performed. Actually, several ergonomic studies have measured the EMG signal amplitude in some of shoulder muscles during certain ADLs such as typing, however, few studies look at the EMG data for rotor cuff muscles.[238-240] Our results suggest that when shoulder is immobilized and protected, the activities such as typing, writing, clicking a computer mouse or holding a light bag do not highly activate the rotator cuff muscles. This finding is in accordance with Long et al.[231] who reported that supraspinatus activity during typing while wearing a sling is less than 15%MVIC. Therefore, those patients who wish to return to activities such as typing or writing in the early phase after rotator cuff repair may be able to do that without placing excessive strain on their repair sites.

Restoring a full range of motion is usually the main goal of rehabilitation in the first two phases of rehabilitation. However, Lovren et al. (2010) [241] in their kinematic study reported that most demanding daily living tasks required less than 80% of the glenohumeral ROM in scaption plane. In other kinematic studies,[242,243] it was noticed that large elbow flexions are needed for many daily living tasks such as combing hair or eating with a spoon. It implies that most of daily living tasks do not need a full ROM of shoulder joint and having a certain level of shoulder abduction with a normal elbow and wrist motion may be enough for performing many of daily activities. In this respect, immobilizing the elbow and wrist joints would only restrict patients to perform some of their routine activities without helping the integrity of their repairs. Our findings provide a scientific basis for some daily activities which are applicable while wearing orthosis.

4.3 Resistance exercises can be started in the first phase of rehabilitation while the shoulder is immobilized.

In most rehabilitation protocols, resistance exercises for shoulder begin when the patient demonstrates adequate passive and active range of motion, and their scapula-thoracic kinematics and compensatory patterns have been improved .[233] Typically, it begins around 12 weeks after surgery compatible with the third phase of rehabilitation. At this point, it is supposed that tendon-to-bone healing can endure the initiation of strengthening exercises.[233] The main target of strengthening exercises are rotator cuff and scapular stabilizing muscles and this type of exercises are performed with elastic bands or weights.[244] However, resistance training for arm and forearm muscles is also postponed to the third phase of rehabilitation. The effect of biceps curl on rotator cuff activity has not been studied before. From previous EMG studies we know that both head of biceps are active during arm elevation and long head of biceps is more mechanically involved in humeral head stabilization.[245] In addition, in both healthy and cuff subjects the activity of biceps was little (less than 5% MVC) during shoulder motion when elbow was fixed by a brace.[246] But what if shoulder is fixed and arm and forearm muscles generate force? Could it harm the repaired cuff tendon? Traditionally patients are discouraged to apply any force to elbow and wrist joints after their rotator cuff operation. How much force can be detrimental to repair in patients is not known. Cadaveric studies have given some idea about the amount of force to failure for the repaired tendon. The force to failure of the cuff repair has been reported between 201 and 302 N[247,248] and this load is compatible with a sudden single pull load caused by a maximal contraction of the repaired cuff (such as MVC). The studies which have shown the failure result following cyclic loading of the repaired tendon have imposed more than 50% of the above mentioned maximal force.[249,250] However, in those studies, the number of repetition to failure changed with the cadavers' age, the suture types and the force direction. Bicknell et al. (2010)[251] reported 50% loss of repair after 206 ± 88 cycles of loading at 44 ± 15 N. Considering this report, Long et al. (2010)[231] modeled the supraspinatus muscle force as the product of MVIC fraction, muscle CSA, specific tension and cosine of the fiber pennation angle and estimated that 15% of MVIC for supraspinatus corresponds to 31 N force. As cyclic loading of this amount may be detrimental to the repaired tendon, they advocated that any activity beyond 15% MVC may impose non-safe amount of force to supraspinatus.

From all these details, I want to conclude that measuring the safe amount of load or force for repaired tendon is not clinically feasible but EMG studies may help us to have an estimation of the safe load. Our findings showed that resistance training of elbow and wrist joints with low loads (2, 4 lbs) would not highly activate the rotator cuff muscles (less than 15% MVC) but create moderate activity level for some other muscles including biceps. It should be noted that such type of exercises might not be applicable in all cases after rotator cuff repair. Some patients with rotator cuff tears may have spontaneous rupture of the long head of biceps[36] and some surgeons prefer to do biceps tenotomy along with rotator cuff tendon repair.[252] In this situation, high activation of the biceps may deteriorate surgical outcomes. Patients with only cuff repair may benefit from resistance exercises of elbow and wrist joints to increase the functionality of their upper limbs and overcome the harmful effect of immobilization. As mentioned before, 4-6 weeks of elbow immobilization could significantly reduce the strength of forearm flexors,[22] and triceps brachii.[253] To reduce these harmful effects, some suggested that even strength training of the non-immobilized limb could be beneficial for the immobilized limb in respect to muscle size and strength.[224,225] We suggest that resistance training for biceps, triceps and forearm muscles in selected cases can be applicable in the first phase after cuff repair.

4.4 Hand gripping with maximal force, may not be safe after rotator cuff repair.

Alternative hand gripping is usually included in early rehabilitation protocols.[156] Forceful gripping usually follows with progression of rehabilitation. A previous study[254] has shown that hand gripping with 30% and 50% MVC would increase supraspinatus activity by nearly 10% maximal voluntary exertion. Other study[255] showed that biceps brachii plays a significant role when gripping. In that study performing shoulder exertions simultaneously with a hand load versus the same load plus a grip resulted in a differential distribution of shoulder muscle activity. A simultaneous static shoulder exertion and 30% MVC hand grip reduced both anterior and middle deltoid activity by 2% MVC and increased posterior deltoid, infraspinatus and trapezius activity by about the same value. These findings suggest that hand gripping may increase the activity of rotator cuff muscles. However, when the gripping transducer was fixed and the subjects did not need to stabilize the arm, reduction in EMG activity of some shoulder muscles such as trapezius has been observed.[255,256] In addition, elbow position can affect the redistribution of shoulder muscle activity when gripping.[255] Our subjects' shoulders were immobilized and their elbows were extended during gripping exercises. In this position, the activity of rotator cuff muscles during alternative gripping exercise with low force (making a fist) was below 5% MVC. So, our study confirms the clinical application of alternative low force gripping during the first phase of rehabilitation. However, when the subjects were asked to do maximal static gripping test, the activity of rotator cuff muscles significantly increased and in some cases overpassed 20%MVC. Therefore, maximal gripping is better to be avoided during the early phases of rehabilitation. Future studies may reveal which force ranges for sub-maximal alternative gripping exercises is applicable in the first phase of rehabilitation.

4.5 Active shoulder adduction exercises with low force do not highly activate the rotator cuff muscles

Abduction immobilizers are widely used for arm immobilization after rotator cuff repair. There is evidence suggesting that vascularization is improved and tension on the repaired tendon(s) is minimized in this position,[44,158] (see also part 2.3.1). In the period of immobilization which may last 4 to 8 weeks, the patient may come out of the immobilizer only for supervised passive motion exercises and active assisted range of motion.[233] Our study suggests that at the end of the first phase of rehabilitation when the active assisted exercises are commenced, patients may be allowed to start arm adduction exercises. In fact, by replacing the abduction hard wedge with a low density foam, the patient can do some type of supported active exercises while wearing the immobilizer. The results indicate that aside from subscapularis, the EMG activities of other rotator cuff muscles were under 20% MVC during adduction exercises with low density foams. In addition, these exercises could highly activate the pectoralis major, latissimus dorsi and triceps muscles. Subscapularis rupture is not very common [11] and is mostly seen in massive cuff tears [54] where more conservative rehabilitation is desirable. For cases with intact subscapularis, active arm exercises may begin earlier with active adduction and passive abduction in certain ranges of motion. Decreased EMG activity of subscapularis muscle has been reported in patients with impingement [257] and anterior shoulder instability.[258] Restoring activity of subscapularis muscle may help improving shoulder dysfunction. Most resistance exercises for subscapularis strengthening such as dynamic hug, diagonal or push up activate both subscapularis and supraspinatus muscles in moderate to high level [259] and therefore, are not appropriate in the early phases of rehabilitation. The selection of an appropriate exercise would safely activate all the desired muscles via light resistance while maintaining low muscle activation levels for the muscles with repaired tendon. The adduction exercises that have been introduced may help patient's upper limb return faster to its normal function. However, we acknowledge that generation of passive tension on the repaired site should be taken into consideration while prescribing such kind of exercises. This issue has been evaluated in our lab by Hearing et al. (2015)[260] through a simulation-based study and they revealed that passive glenohumeral elevations below 25° or above 75° may exceed the safety zones. So, if the adduction exercises can be kept in this glenohumeral ranges, they may impose low tensile stress on the repaired tendon. Therefore, in specific situation such as repair of an isolated supraspinatus tear or when minimal tension has been imposed to re-attaching the tendon, such active arm adduction exercises can be added to a dynamic rehabilitation protocol.

4.6 Active arm abduction imposes more stress on supraspinatus than active scaption and flexion

Active shoulder ROM exercises usually begin near the end of the second phase of rehabilitation. It was reported that full forward elevation is restored by 3 months for small tears vs 6 months for medium and large tears.[261] Therefore, performing this type of exercises may last a couple of weeks before achieving the full ROM. Active arm elevation exercises are usually prescribed in different planes and angles, but the sequences of elevation in respect to plane and arc of elevation has not been identified. Most studies on plane of elevation have been performed by kinematic analysis and no electromyographyic study has comprehensively examined shoulder musculature during arm elevation in cuff patients to determine if the plane of elevation influences shoulder muscle activity pattern. Our last study which was presented in the third article, to the best of our knowledge is the first study on a patient population with cuff tear that concomitantly analysed both EMG activity of shoulder musculature and kinematics of arm elevations in different planes. According to our results, supraspinatus activity is considerably higher in abduction position than scaption and flexion respectively. This might indicate that active ROM exercises in abduction plane might impose more stress on repaired supraspinatus tendon. The present finding is different from what has been reported before on normal population in that supraspinatus had a similar activity level during abduction, scaption and flexion.[262] Biomechanical studies have shown that kinematics of clavicular, scapular and humeral motions during arm elevation are different in abduction and scaption[62] and supraspinatus has greater elevation moment during abduction than scaption.[263] Therefore, our EMG results may reflect these biomechanical findings, although we cannot explain how the moment arm might be affected by tendon tear.

It should be mentioned that there is still controversy regarding the proper timing of active ROM after rotator cuff repair. Active arm elevation can be customized early (3-4 weeks after repair) or delayed (6 weeks after repair) based on the rehabilitation protocol. At 16 weeks after rotator cuff repair, Duzgun et al. (2011)[143] found that patients with early active ROM had less pain during activity and better functional outcomes compared with those who received delayed active ROM exercises. Klintberg et al. (2009)[141]had also reported better pain control in the early AROM group, 2 years after surgery. However, Kluczynski et al. (2015)[153] in their meta-analysis compared rotator cuff healing rates in patients with early *versus* delayed active ROM regimens and found higher risk for structural defect in early AROM groups. Our results suggest that irrespective to the early or delayed approaches, active arm elevation is better to begin in flexion plane and gradually progress to scaption and abduction planes to provide safer level of stress on the repaired tendon of the supraspinatus.

4.7 LIMITATIONS AND CHALLENGES

4.7.1 Kinematic studies in patients with rotator cuff pathology

Elevation angle in clinical setting is usually measured by goniometer and the angle between arm and thorax is calculated. Although this method is very practical for clinical purposes, it lacks enough precision for biomechanical studies. Arm elevation is the result of interaction between sternoclavicular, acromioclavicular and glenohumeral joints and the scapulothoracic pseudo-joint. Conventional methods usually calculate thoracohumeral angle without considering scapular movement that directly affects the glenohumeral joint orientation.[264] Patients with rotator cuff pathology have altered shoulder kinematics in an attempt to avoid pain or impingement of the cuff tendon. Arm elevation in this patient population is often affected by dysfunction of the shoulder musculature and scapular dyskinesia.[265] For example, in patients with rotator cuff pathology, posterior scapular tilt increased during arm elevation,[266] or symptomatic patients with full rotator cuff tears exhibited a greater scapular elevation even with a simple elevation movement.[267] Actually scapula may be elevated or rotated to a greater degree to reduce the requirement for elevation at the glenohumeral joint. Therefore, comparing two cuff patients according to their thoracohumeral angles may be misleading because two patients with similar thoracohumeral elevation angles may have different glenohumeral contributions. As rotator cuff acts mainly on glenohumeral joint, the ranges of glenohumeral angle should be more influenced by rotator cuff pathology. By using three-dimensional motion analysis, researchers can measure different orientation of the joints such as thoracohumeral, glenohumeral, and scapulothoracic as well as the sternoclavicular and acromioclavicular. A three-dimensional motion analysis can dynamically calculate glenohumeral contribution during arm elevation and provide more accurate measurements especially in patients with rotator cuff pathology and altered shoulder kinematics. However, this type of measurement is difficult to perform and needs special technologies which may not be applicable in clinical setting. Reporting the arm kinematics according to glenohumeral angles provides the advantage of more accurate computation, but it gives less meaningful information regarding the position of the arm. So, in most kinematic studies in patient population there is a challenge between practical application and precision. We decided to use a 3D measurement system to present more precise data in our third study. However, we presented both maximal thoracohumeral and glenohumeral elevation angles to help clinicians estimate the position of arm in relative to the trunk for each patient.

4.7.2 Normal subjects may not represent patient population

The main limitation of the researches presented in this dissertation is that most of our findings which were presented in the two first articles have been revealed from normal healthy subjects who may not represent the patients with rotator cuff tears. However, it should be noticed that most of the persisting data in the field of rehabilitation is derived from studies on healthy subjects. (see Table 5, page 67) EMG studies on patients with rotator cuff pathology face with some limitations. First, pain by itself can influence the EMG activity of the affected muscles. For example it was observed that when the subjects with neck pain did the high force contraction, the increase in non-normalized, root mean squared EMG of trapezius muscle was lower in the painful side.[268] Second, the factors such as muscle damage, fat infiltration, muscle atrophy and muscle contractibility may change the characteristics of the EMG data in this patient group, so larger variability may result. Third, symptomatic patients may be unable to generate maximal voluntary contractions; or maximal contraction may not be safe for patients with rotator cuff tear or after rotator cuff repair. Therefore, quantifying the EMG data in patient population is challenging, and although some EMG studies on cuff patients have used MVIC for normalization of their data, the accuracy of their EMG interpretation is under question. For example, Reddy et al.(2000)[257] reported that the activity of middle deltoid and rotator cuff muscles in subjects with subacromial impingement was most notably decreased in the first arc of motion. In this study, the EMG data has been normalized by the values derived from maximal manual tests. However, the researchers reported that they had to modify the test position for the patient group to avoid pain provocation. Did modifying the test position affect the MVC values? This question has not been answered in this study. In another study conducted by Kelly at al. (2005),[269] the EMG data of 12 patients with two tendon cuff tears has also normalized by MVIC. All subjects which were half symptomatic and half non-symptomatic did the same manual testing to produce maximal contraction. For example, according to the authors, supraspinatus activity was tested by resisted arm elevation at 90° in scapular plane, 45° internal rotation and elbow extension. Whether a symptomatic patient with low functional score can do the maximal contraction in this position is under question. These limitations led some researchers to use the other methods of normalization especially for patients with massive rotator cuff tear. For example, to evaluate the shoulder muscle coordination in patients with massive cuff tear, Steenbrink et al. (2006) [217] normalized the EMG by peak values while Hawkes et al. (2012)[270] used mean values for normalization. Normalisation by either the peak or mean values considerably reduces the variation of the activity pattern; however, information about the absolute signal may be sacrificed.[193] Considering all the challenges for studying on patients with rotator cuff tear, most researchers prefer to test the rehabilitation exercises on young healthy subjects.

4.7.3 Pre-op patients may not represent post-op patients

Our third study has been performed on a group of patients with rotator cuff tears who were in the waiting list for rotator cuff surgery. We evaluated the EMG of shoulder musculature in those patients to see how elevation tasks in different planes and arcs would recruit muscle activation. However, whether the pre-op muscle activity pattern can be applied to post-op shoulder muscle activity, is not known. De Witte et al. (2014) [271] tried to reply to this question. They quantified the contribution of the rotator cuff to arm abduction in cuff tear patients before and one year after surgical cuff repair. They assessed the changes in deltoid activation in response to variations in arm abduction moment loading, assuming that rotator cuff repair will decrease the compensatory deltoid activation. After surgery, the average deltoid activity in patients slightly decreased but no statistically significant differences with pre-operative measurement was observed. From this observation they concluded that the rotator cuff activity will restore partially – but not completely, one year after repair. Although in this study the EMG activity of rotator cuff has not been directly measured, the assumption of authors regarding the compensatory higher activity of deltoid in cuff patients has been well documented. In fact, the complementary role of supraspinatus and deltoid during arm elevation has been studied by nerve blocking,[272] in cadaver,[273] computer models[274] and in patients with rotator cuff tears,[217] all have suggested that disruptions in the normal function of some rotator cuff muscles would place a higher demand on deltoid and result in an increase in deltoid activity. Persistence of compensatory mechanisms one year after repair may indicate that amelioration of compensatory mechanisms is a gradual phenomenon. Using this concept, it is assumed that the muscle activity pattern of the patients in our study would not dramatically change after 4 to 6 weeks of operation. Although direct measurement of rotator cuff activity pre and post-surgery would certainly provide more precise information, EMG study of rotator cuff muscles in early post-op period may not be feasible. The invasive technique of electrode insertion may ethically and technically limit EMG studies in this period. Moreover, it is more reasonable to assume that muscle activity pattern in patients shortly after rotator cuff repair is more similar to patients with rotator cuff tears than normal subjects. However, proving this assumption needs additional studies.

4.7.4 There is not a unified definition for 'safe exercise' after cuff repair

One of the major challenges in rehabilitation studies is the definition of 'safe exercise'. Actually the definition of safety is not clear in the rehabilitation literature. In the clinical settings, any exercise that does not endanger the repair and does not provoke the patient's symptoms can be considered safe. But in scientific world, how can we quantify the stress level and determine the threshold for safety? Many authors assumed exercises that minimally activate the rotator cuff muscles co be considered safe post-operatively (see section 4.1.1) High and low muscle activities in EMG studies have been arbitrarily classified according to the percentage of MIVC. In this classification, any EMG record of less than 20% MVIC is considered low activity for the muscle. Although this classification lacks precision, it can help in quantifying muscle activity and comparing different rehabilitation exercises. As described before, this classification may not be applicable for patients with rotator cuff pathology, before or after rotator cuff surgery. In addition, EMG amplitude indicates the state of activation of the contractile element, which may be different from the tension recorded at the tendon. Actually, besides muscle activation, other factors such as tendon lengthening during full ROM may increase tendon stress.[260] However, despite all limitations of this method, it is widely used in clinical studies and has provided scientific basis for many rehabilitation regimens.

The other method for evaluation the safety of an exercise is to check the repair integrity by ultrasound or MRI after applying an exercise regimen.[12,60,145,147] Although evaluating the anatomical integrity of the repair seems a more accurate method, its usability is limited. First, MRI studies are very expensive and ultrasound studies are highly user- dependent. Second, some symptoms such as pain and functional score may not be directly related to the anatomical integrity of the repair. This issue has been shown by Flurin et al. (2007) [60] in their study on 576 cases after arthroscopic rotator cuff repair whose Constant score were dramatically improved one year after surgery despite incomplete tendon healing in imaging studies. Galatz et al.(2004) [12] have also observed good functional scores in 72% of patients with recurrent defect at a minimum follow-up of one year. So, if an exercise would not provoke patient's symptoms or deteriorate their functionality but cause a gap in the repair, should it be considered non-safe? In real world, the clinicians do not follow the repair integrity by MRI or US until the patient is symptomatic. This contradiction, limit the applicability of imaging as a useful tool for determining the safety of a rehabilitation exercise. In addition, detecting a defect does not indicate the causing factor. In fact, besides the rehabilitation regimen, many other factors such as age, diabetes, smoking habit, the chronicity of the tear, technique of repair, tear size, fat infiltration and so on can influence on repair integrity.

Different biomechanical models[163,275] have also been created to help determining the safety of a special positioning or exercise. Generally, two different methods are widely used to estimate muscle stress and force in musculoskeletal shoulder models: Stress-based methods and EMG-based methods. The stress-based method is using a constrained optimisation algorithm related to a stress-based cost function. In these optimization-based inverse-dynamics musculoskeletal models, force is estimated indirectly from the moments produced by an entire group of muscles. EMG-based methods use the experimentally measured electric muscle activation to estimate muscle forces through EMG data tracking. Both methods can somehow estimate the stress levels, but stress- based methods are more commonly used. Actually, despite introducing some good shoulder models using EMG-based methods,[276,277] the complicated mathematical measurements limit their clinical application.[278] Stress-based method has also some limitations; for example, they may overestimate the problem of glenohumeral stability.[278] How exactly these models can simulate the real situation, needs also further studies.

In vivo measurement of force for an isolated muscle such as supraspinatus is one of the biggest challenges in biomechanics. In fact, multiple muscles span shoulder joint and the joint moment can be the result of different muscle excitation strategies. The possibilities to measure muscle forces in vivo are limited, because the invasive methods can be performed just in operating rooms and non-invasive methods can only provide information on the forces exerted by groups of muscles not the individual muscle. So, we do not know how much force or stress could an individual exercise impose on the repaired tendon, and in what level, this force can be detrimental. Cadaveric studies[95,249,251] have provided valuable information to determine the level of force to failure. But it may not represent the situation in an alive human body. Animal studies have been also the basis of many rehabilitation protocols in respect of safety, (see section 2.2.2). Although animal studies provided valuable information about the healing timing and process and the effect of general mobilization on healing, they are limited in case of specific exercises that are applicable only on human bodies.

In summary, safety for a rehabilitative exercise has not been clearly defined and this limits the interpretation of many research data in term of clinical applicability. So, if I am asked whether the exercises that are presented in this dissertation are really safe, my response cannot be frankly positive or negative. We introduced some movements that could minimally activate the rotator cuff muscles (less than 20% MVIC). Our findings are based on the assumption that higher activity of rotator cuff muscle may produce more force within the muscle that may cause more stress on the related tendon. This assumption has been the basis of many rehabilitation exercises but it can be confirmed only by the well-designed clinical trials. Until reaching to a consensus on the definition of safety, the methods such as EMG, imaging, simulation models, cadaveric and animal models can provide useful information for clinicians to estimate with higher precision the safety level of the rehabilitation exercises.

4.8 DIRECTION FOR FUTURE RESEARCHES

4.8.1 Comparing immobilization and semi-immobilization in patients.

In articles 1 and 2 we suggested that the patient's upper limb can be semi-immobilized in a special type of orthosis after rotator cuff repair and some ROM exercises as well as light resistance exercises may be applicable in this semi-immobilization period. These suggestions are based in our studies on normal population. Additional research is needed to see if the suggested modifications of abduction shoulder orthoses is applicable in real life for patient population. Future studies should determine if movement of elbow and wrist joints can affect the healing process, patients' symptoms and restoration of their normal function. In addition, the level of comfort for this type of orthoses should be investigated.

4.8.2 Determining the safe load and fatigability of shoulder muscles in patients

Although in the second article we suggested that 2-4 lbs load may be applicable for resistance training during semi-immobilization period, we could not determine if this range of loading is really safe for the patients after cuff repair. Future studies should work on the proper load and the number of set for resistance training in patient population to determine the safe quantity, timing and repetition of resistance exercises in this patient group. In addition, we found that maximally squeezing of medicine ball produced high activity of rotator cuff muscles but low force repetitive gripping was not highly provocative for cuff muscles. The effect of sub-maximal gripping force on the activity of rotator cuff muscles should be studied in the future.

Muscle fatigue in post-op patients is also important to be studied specially after resistance training and the ADLs that created low rotator cuff activity. EMG is a good tool to investigate muscle fatigue and the median frequency slope can be used as a fatigue index. Greater fatigue was observed in the deltoid and rotator cuff muscles in healthy subjects during isometric arm elevation tasks.[279,280] Hawkes et al. (2015)[281] studied the fatigability of shoulder musculature in patients with massive cuff tears and observed greater fatigue in anterior and middle deltoid but interestingly no significant fatigue in the rotator cuff muscles. Perhaps rotator cuff muscles – while contracted against a torn tendon – could not develop appreciable force. But what if the tendon is repaired? How long a light resistance training or a light daily activity can be continued without fatigue, and in which muscles or muscle groups in post-op patients we expect to see more fatigue? Hopefully future studies will answer these questions.

4.8.3 The shape and texture of wedges for adduction exercises

The idea of positioning a wedge shaped foam under the arm that we introduced in this dissertation was preliminary. More works needed to be done to identify the best angle of abduction and the proper ranges for adduction exercises. In addition, it might be useful to compare the adduction exercises with and without foams in respect of muscle activity, patients' comforts and functional outcomes. Besides, future studies should evaluate the tensile stresses on the repaired tendon during adduction exercises. We acknowledge that while adduction exercises may be potentially safe from a loading perspective, they may not be safe in terms of generation of passive tension. However, as mentioned before, the range of 25° -75° of glenohumeral elevation may be considered safe in respect of tensile stress.[260]

4.8.4 Consensus on normalization method for EMG studies in patient population

As deliberated before, one of the main concerns in rehabilitation studies is how to compare the EMG studies of rotator cuff patients. Presently it is challenging for two following reasons. First, many of studies on patient population are lacking the precise definition of underlying pathology. Patients with shoulder pain may have different diagnoses. Shoulder impingement syndrome consists a variety of pathologies including, bursitis, tendinitis or tendon tear. In this respect, our third study which has been done on a small group of patients with full thickness rotator cuff tears is well harmonized. But better harmonization could be achieved if the other important factors such as muscle quality and tear chronicity could be taken into consideration. In addition, the compensatory mechanism may differ in different patients and therefore, high variation in muscle activity patterns have been reported in EMG studies of patients. Second issue is the variation in normalization method for interpreting the EMG data. As it was explained before, although MVIC is the most popular method for normalization and quantifying of EMG data in normal population, it is not applicable in symptomatic patients or for studies in patients after rotator cuff surgery. Using different normalization methods made a barrier for comparing between studies performed on patients. This issue needs to be addressed in future consensus meetings of international biomechanics/ EMG or rehabilitation organizations.

5 CONCLUSIONS

Torn rotator cuff tendon is surgically repaired to decrease patient's pain and increase their ROM and functionality. Post-operative rehabilitation after rotator cuff repair plays a significant role for the ultimate outcome. Post-surgical care should balance between the restrictions applied for tissue healing and the exercises prescribed for restoring range of motion and muscle strength. Quiet number of surgeons discourage early active mobilization of shoulder joint, in fearing of deleterious effect of early mobilization on tendon repair. Due to this concern, most rehabilitation protocols include a period of shoulder immobilization during which only passive range of motion is allowed to be performed. The exercises are gradually progressed to active range of motion until the full range of motion is achieved around 12 weeks post-operation. This dissertation introduced some exercises that could be applicable in this period of rehabilitation before initiation of resistance training exercises for rotator cuff muscles.

From the persisting data, it may be concluded that highly conservative rehabilitation approach may lead to shoulder stiffness, muscular weakness and prolonged rehabilitation that postpone the patient's upper arm functionality. The relationship between repair and patient' symptoms is complex. Despite adequate repair, some patients may still have pain and stiffness[282] and pain improvement has been reported in patients even with some percentage of gap in their repair.[60] Understanding the pathophysiology of rotator cuff tears may help to realize how to balance the repair safety with symptoms improvement. Arthroscopic rotator cuff repair with less muscle damage and improvement of repair techniques provided an opportunity for more aggressive rehabilitation approach. Rehabilitation after cuff repair based on several factors, such as patient's age, tear size, tissue quality, and surgical technics. I believe that in certain cases (such as smaller tear, better tissue quality, and younger ages) some modifications in routine rehabilitation regimen can be applied to decrease the risk of stiffness and increase the functionality of the patient's upper limb. A summary of our suggestions has been presented in Table 6. These modifications include:

- **Active mobilization of elbow and wrist joints while shoulder joint is immobilized.**

We showed that active mobilization of elbow and wrist joints can minimally activate the rotator cuff muscles. Specific shoulder orthoses can be designed to adjust the immobility of shoulder with mobility of elbow and wrist joints. Fortunately, at the time of writing this thesis, few dynamic shoulder orthoses have been introduced in the market and our findings could provide a scientific basis for the modifications applied. Hopefully future studies will clarify the efficacy of this type of orthoses. We suggest that during the shoulder immobilization period, elbow and wrist joints can be mobilized without stressing the repaired tendon.

- **Performing some daily living activities while wearing shoulder orthosis**

We showed that some daily activities such as working with a computer would minimally activate the rotator cuff muscles. Therefore, clinicians may advise their patients regarding the appropriate daily activities that probably impose low stress on their repaired tendon. The activities such as typing, writing, clicking and holding light weights may be safe to be performed while wearing shoulder orthosis, however, how long or how many cycles a patient can continue these types of activities before reaching to fatigue state needs further investigation.

- **Light resistance training for elbow and wrist joints while shoulder is immobilized**

Although strength training for rotator cuff muscles should be postponed until the repaired tendon achieves enough strength to cope with the loading, resistance training of elbow and wrist joints does not impose high stress on the repaired tendon. We suggest that some resistance training may be applicable in the early phases of rehabilitation without highly involving rotator cuff muscles. Such exercises include isotonic contractions of arm and forearm muscles with 2-4 lbs loads, wrist flexion/ extension exercises with 2-6 lbs load and alternative forceless or low force hand gripping. However, safe load cycling of such resistance exercises should be determined by future studies.

- **Shoulder adduction exercises with soft wedges while wearing shoulder orthosis**

Adduction exercises can be introduced to some selected patients with intact biceps and subscapularis when active assisted range of motion exercises are planned. Low resistance foams facilitate contraction of adductor muscles as well as subscapularis, while supraspinatus and infraspinatus are less active. In fact adduction exercises can isolate subscapularis activation without imposing more stress on supra and infraspinatus muscles. In this form of exercise, arm abduction is followed passively, with minimum activity of cuff muscles. Identifying the best angle ranges for adduction exercises and the safe tensile load that can be imposed on the repaired tendon needs further investigation.

- **Sequencing and progressing the active arm elevation exercises from flexion plane to scaption and abduction planes respectively.**

We showed that in patients with cuff tears, activation of supraspinatus significantly differ in the three planes of abduction, scaption and flexion. In the late second phase of rehabilitation, when patients begin AROM, plane of elevation can be chosen wisely in order to gradually increase the activity of cuff muscles. Our suggestion is a progressive sequence of flexion, scaption and abduction exercises after supraspinatus repair. However, for isolated infraspinatus repair, the sequencing of arm elevation according to the elevation plane may not be necessary.

Table 6: Suggested modifications to the early phases of rehabilitation

Rehab Phase	Conventional method	Suggested Modifications
Protection	Complete Upper Limb Immobilization  - Passive ROM + Pendulum Exercises + Periodic mobilization of elbow/wrist - No Resistance Training	Semi-Immobilization of the Upper Limb: • No immobilization for Elbow, Wrist, Fingers • Loaded mobilization of elbow/wrist (up to 4 Ibs) • Grip exercises with low force • Performing some daily living activities • Shoulder adduction exercises in certain cases 
Restoring ROM	ROM Exercises without any specific order 	Order for Elevation Exercises For supraspinatus (SS) tear: • Sequencing the elevation exercises: Flexion, Scaption, Abduction For infraspinatus tear: • No plane effect • Slow progression in elevation arc

Clinicians expect to see a good progression in the first 12 weeks after rotator cuff repair in term of controlling the pain, stiffness and active range of motion to prepare their patients for more advanced phases of specific strengthening and functional exercises. We believe that our findings that deliberately discussed in this dissertation can help clinicians to design more efficient rehabilitation programs for their patients' preparation. In addition, we hope that the functional rehabilitation approach that we suggested here, can help the patients to have better quality of life and self-imaging during the recovery period.

The End

Nov 2015

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7 APPENDICES

Appendix 1: Classifications of rotator cuff tears

A: Tear Classification

Bateman, 1963:[283] length of the greatest diameter of the tear

Small: less than 1 cm

Medium: 1-3 cm

Large: 3-5 cm

Massive: more than 5 cm

Neer, 1983: [36] pathology of the lesion

Stage I: edema and hemorrhage of the tendon and bursa, occurs in < 25 years

Stage II: tendinitis and fibrosis of the rotator cuff, in 25- to 40-year-olds

Stage III: tearing of the rotator cuff (partial or full-thickness) in those > 40 years

Patte, 1990:[284] topography of the rotator cuff tear in MRI, and the level of cuff retraction.

Grade 1: full-thickness tears with little tendon retraction, tendon between the greater tuberosity and apex humeri

Grade 2: retraction of tendon to level of humeral head, tendon between apex humeri and glenoid

Grade 3: retraction of tendon to level of glenoid, tendon medial to glenoid

Ellman, 1990:[285] location, depth, and area measured arthroscopically

Partial thickness tears:

Grade I: tears had a depth of less 3mm

Grade II: Tears with depth of 3 to 6 mm

Grade III: tears with depth more than 6 mm

A: articular surface, **B**: Bursal surface, **C**: interstitial

Full thickness tears:

Grade	**Size**	**Description**
I	Less than 2 cm	Small
II	2-4 cm	Large
III	More than 4 cm	Massive
IV		Cuff arthropathy

A: Supraspinatus, **B**: Infraspinatus, **C**: Teres minor **D**: Subscapularis

The tear size is estimated in sagittal plane.

Harryman et al. 1991:[89] location and no. of tendon torn

Type 0: intact cuff

Type IA: partial tear

Type IB: full thickness supraspinatus tear

Type II: full thickness supraspinatus and infraspinatus tear

Type III: full thickness supraspinatus, infraspinatus and subscapularis tear

Snyder, 1991:[80] location and severity of the lesion

A: Partial articular side, **B**: partial bursal side, **C**: complete

Partial tears

0: normal cuff with smooth coverings of synovia and bursa

I: minimal superficial bursal or synovial irritation or slight capsular tear in a small localized area, usually < 1cm

II: Actually fraying and failure of some rotator cuff fibers in addition to synovial, capsular or bursal injury usually < 2cm

III: More sever rotator cuff injury, including fraying or fragmentation of tendon fibers. Often involving the whole surface of a cuff tendon. Most often the supraspinatus; usually < 3cm

IV: Very severe partial rotator cuff tear that usually contains, in addition to fraying and fragmentation of tendon tissue, a sizable flap tear and often encompasses more than a single tendon.

Complete tears

C/0: partial articular and bursal tear

C/1: Full thickness tear less than 1 cm

C/2: Full thickness tear, 2-3 cm, only involve supraspinatus, minimal retraction

C/3: Tear involving the supraspinatus and part of infraspinatus tendon

C/4: Massive tear involving at least two tendons

Masten et al, 2008:[69] extent of the lesion and the structures involved

Stage I: full thickness supraspinatus tear (=< 2cm)

Stage II: full thickness supraspinatus and partial infraspinatus tear (2-4 cm)

Stage III: full thickness supraspinatus, infraspinatus and subscapularis (5cm)

Stage IV: cuff tear arthropathy

Davidson & Burkhart, 2010:[286] arthroscopic identification of the shape of the lesions

Crescent shaped: usually do not retract medially, are quite mobile in the medial to lateral direction, and can be repaired directly to bone with minimal tension.

U Shape: Similar shape to crescent but extend further medially with apex adjacent or medial to the rim of the glenoid. Must be repaired side-to-side using margin convergence first to avoid overwhelming tensile stress in the middle of the rotator cuff repair margin.

L or reverse L shape: Similar to U shape except one of the leaves is more mobile than the other. Use margin convergence in repair.

Massive, Immobile: May be u-shaped or longitudinal. Difficult to repair and often requires and interval slide.

B: Side effects

Goutallier, 1991:[16] Classification of fatty infiltration based on the presence of fatty streaks within the muscle belly using CT imaging, and later on applied to MRI too.

0: Normal

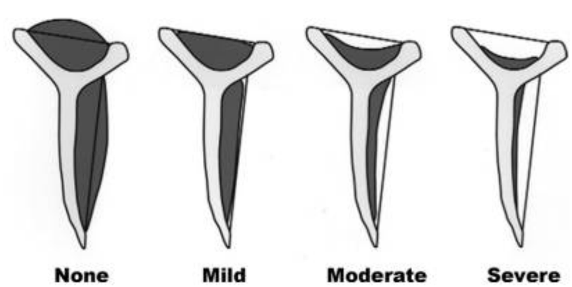
1: Some fatty streaks

2: More muscle than fat

3: Equal amounts fat and muscle

4: More fat than muscle

Warner et al. 2001:[287] Grading scale for muscle atrophy based on the oblique sagittal-plane of MRI. According to the relation of the muscle to a straight line connecting either the coracoid to the scapular spine (assessing the supraspinatus) or the coracoid to the tip of the scapula (assessing the infraspinatus).



Appendix 2: Fine wire electrode insertion techniques for rotator cuff muscles

The information in this part has been derived from the instructions in Standard Operating Procedure prepared by Rebecca Brookham from Waterloo University.

For evaluating the activity of rotator cuff muscles, single-use hypodermic needles is inserted through the skin in each of the four rotator cuff muscles. All skin in the area surrounding the insertion sites should be cleansed with isopropyl alcohol or betadine, and the researcher should wear sterile glove at all time during insertion procedure.

Insertion placement for supraspinatus:

Subject's position: prone, arm at the side

Point of insertion: Localize medial one third of scapular spine. Insert needle 2 cm above this point. Needle should be inserted parallel to skin toward your finger that overlays the scapula spine, into the suprascapular fossa. Be sure that the scapular bone is beneath insertion side to avoid the risk of pneumothorax. Needle will pass through middle trapezius before inserting in supraspinatus.

Test: ask the subject to abduct the arm against resistance. Check EMG signals.

Insertion placement for infraspinatus

Subject's position: Prone with arm at the side

Point of insertion: Landmark scapular spine, medial and lateral borders and find centre of infraspinatus fossa. Insert needle into centre of infraspinatus fossa (halfway between scapular spine and inferior angle, midway between lateral and medial borders). The needle should pass middle trapezius before reaching to infraspinatus. Try to capture the inferior border of scapula with your thumb and index fingers of the non-dominant hand to find easily the center of infraspinatus fossa.

Test: with resisted external rotation, you expect to see good signals. Ask the subject to perform scapular retraction, if you doubt that your electrodes are in mid trapezius.

Insertion placement for subscapularis

For electrode insertion into the subscapularis, three notes should be considered. First, electrodes can be inserted either through lateral border (axilla) or medial border. We preferred medial border insertion technique for our subjects. Second, the subject can be in prone position or in a sitting position. Third, as innervations of upper and lower subscapularis muscle are different, some researchers prefer to use two needles to evaluate the activity of both upper subscapularis and lower subscapularis. In our studies, we checked only the activity of lower subscapularis. The method that we used in our lab is as following.

Subject's position: prone, hand behind the back (approximately level of L5), causing scapula to wing.

Point of insertion: Localize inferior border of scapula, follow the medial border of scapula approximately 3 finger breadth. Insert the needle horizontally toward the subscapularis fossa (anterior of scapula) for about 10 mm and then steer the needle in the opposite direction away from ribcage and toward the scapular bone. Needle will pass through middle trapezius, rhomboids and possibly serratus anterior before reaching to subscapularis.

Test: resisted internal rotation causes good signals, you should observe low activation during scapular retraction.

Insertion placement for teres minor

Subject's position: prone, arm relaxed at side

Insertion point: on lateral border of scapula, find the midpoint between acromion and inferior angle of the scapula. Try to palpate the lateral border with your fingers and insert the needle immediately lateral to this border at that midpoint. Insert the needle at the similar height as infraspinatus insertion.

Test: resisted external rotation causes large EMG activation.