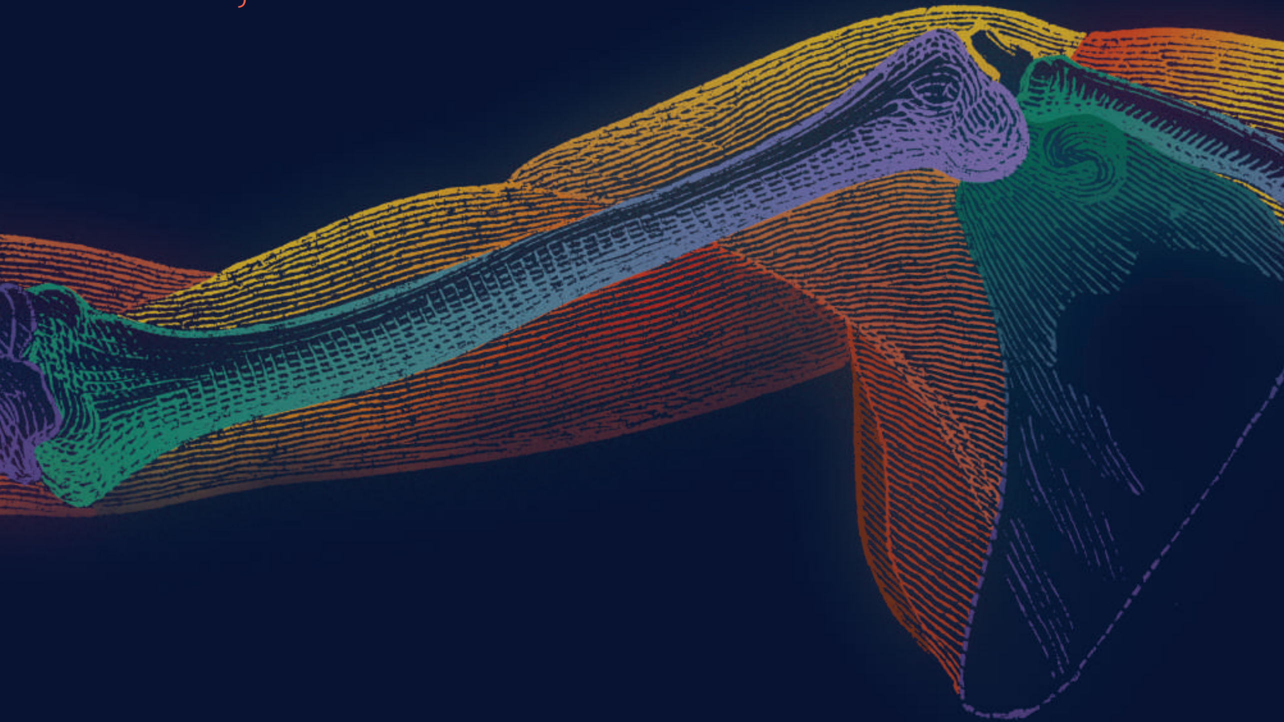
Functional Implications of Structural "Anomalies" in Shoulder Pain

Arjen Kolk



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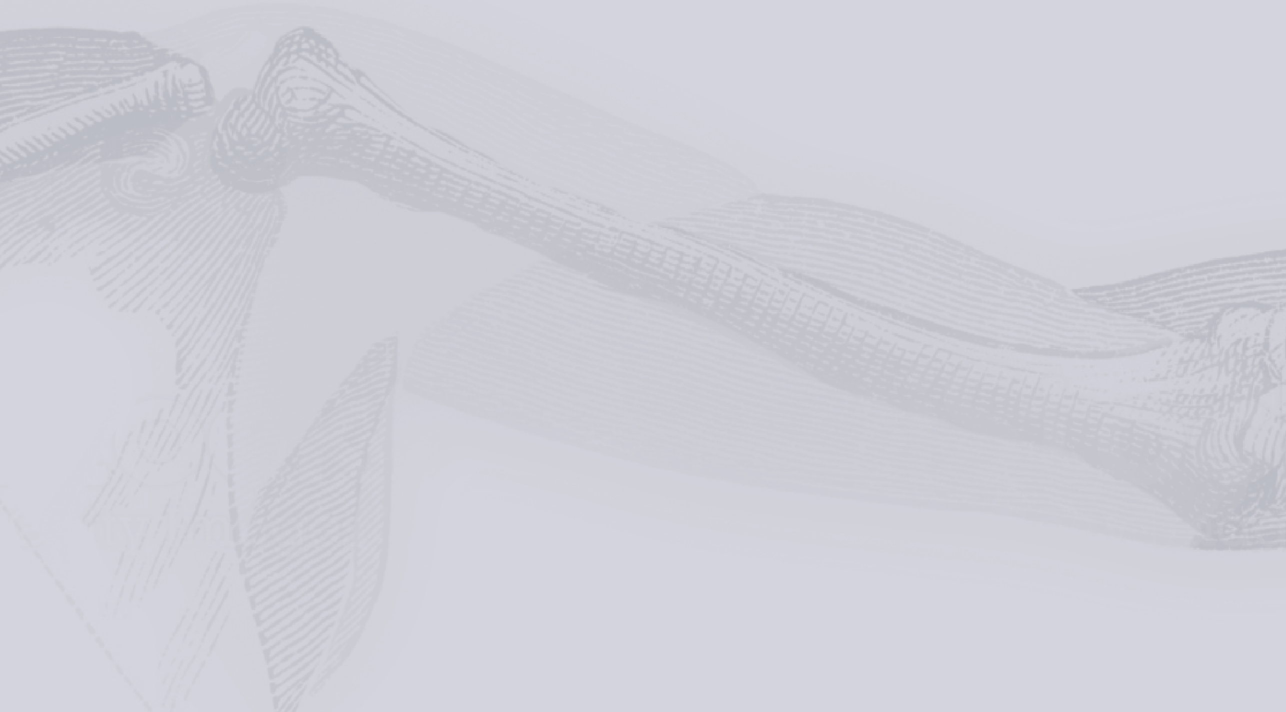
“De grootste vriend van de wetenschap is de twijfel”
Jan Terlouw
in Buitenhof
28 september 2014

CONTENTS



1

General introduction

SUBACROMIAL PAIN SYNDROME

Background

The shoulder girdle is essential to complete our daily life activities. It enables us to complete our tasks by positioning the hand into the space around us. Interestingly, we are usually unaware of the great mobility it requires to eat and wash, until we experience shoulder pain or discomfort. The shoulder movements are created by a complex synergy of motions of the thorax, clavicle, scapula and humerus. The bones are connected at the sterno-clavicular joint, the acromioclavicular joint, the scapulothoracic gliding area and the glenohumeral joint. The glenohumeral joint is a ball-in-socket joint that contributes to the majority of shoulder motion when elevating the arm.[8] Forces generated by scapulothoracic, humero-thoracic and scapulohumeral muscles like the latissimus dorsi, teres major, pectoral major muscle, serratus anterior, deltoid muscle and the rotator cuff (i.e. teres minor, infraspinatus, supraspinatus and subscapularis muscle) all facilitate arm movements.

The shoulder joint is after the low-back the second most reported anatomic site of musculoskeletal pain in Dutch adults.[100] The prevalence of shoulder complaints is approximately 48 per 1000 person-years.[43, 94] Incidence rates are about 11 to 29 per 1000 person-years, with the highest incidence between 40 to 65 years.[7, 43, 122] The most likely origin of shoulder complaints largely depends on age. At younger age (under 35 years), shoulder complaints are frequently caused by glenohumeral instability or a shoulder sprain.[72] In patients over 35 years of age, complaints are more commonly attributed to a supposedly painful subacromial inflammation of the bursa or rotator cuff.[72, 122, 123] Interestingly, the age-dependent cause of shoulder disorders is also reflected by the prevalence of rotator cuff tears, with a prevalence of 3 percent at the 4th decade, 25 percent at the 6th decade, to over 50 percent at the 8th decade of life.[90, 116, 127]

Historical Perspective

At the beginning of the 20th century, the clinical entity and aetiology of shoulder pain was studied by several authors.[16-18, 39] According to these authors, it was evident that inflammation of subacromial structures resulted in pain with arm abduction at the anterior edge of the acromion.[16, 33, 39] As early as 1909, anatomic considerations led to the assumption that repeated mechanical impingement under the acromion could cause painful irritation of the bursa.[12, 39] In these years, Codman extensively published his personal views on shoulder pain. He reported on patient characteristics, the physical examination and symptoms which characterised the clinical entity of a supraspinatus rupture.[17] In an attempt to understand the aetiology of the painful shoulder, Codman further discussed several hypotheses explaining subacromial inflammation, while discussing attrition of subacromial tissues under the acromion as one possible mechanism for pain and rotator cuff tears.[18] Codman was not convinced that a traumatic event caused a supraspinatus rupture. He argued that an "underlying degenerative process" could make the tendon more prone to rupture.[18]

The theory of attrition of structures under the acromion was the reason for Charles S. Neer to introduce the anterior acromioplasty in 1972.[92] Neer concluded that such an impingement occurs at the anterior edge of the acromion rather than the lateral aspect of the acromion.[92, 93] Adjacent to bony morphology, the coracoacromial ligament was assumed to contribute to extrinsic compression.[49, 92] Neer distinguished three stages of "shoulder impingement syndrome": stage I associated with subacromial edema, stage II associated with a partial tear or tendinitis, and stage III associated with a rotator cuff tear.[93] The cause-effect relation of acromion morphology and rotator cuff disease was further propagated by Bigliani.[4, 5] Bigliani argued that more acromial slope was correlated to a higher prevalence of rotator cuff tears.[4] Interestingly, neither physical exam nor radiographic evaluations were able to distinguish between bursitis or a partial thickness rotator cuff tear from the presence of a rotator cuff tear according to Neer's classification.[92, 98] Authors also noticed that radiographs frequently did not show pathology which could be associated with shoulder pain.[38] Nevertheless, the subacromial impingement syndrome was now considered as one clinical entity and Neer's classification was widely accepted among orthopaedic surgeons worldwide. As a consequence, biomechanical and intervention studies studied patients with shoulder impingement syndrome from stage I to III as one entity without additional imaging of the rotator cuff to separate a tendinitis from a torn rotator cuff.[9, 10, 37, 41, 42, 44, 45, 47, 70, 75, 78, 82]

Consistent with the propagation of the attrition theory, the number of anterior acromioplasty (i.e. subacromial decompression) dramatically increased in the nineties and beginning of the twenty-first century.[60, 97, 125] During this procedure the anterolateral undersurface of the acromion was removed to flatten the anterior process of the acromion.[92] Although successful results after acromioplasty have been reported in cohort studies[6, 11, 30, 106], randomised controlled trials were unable to demonstrate the beneficial treatment effect of acromioplasty compared to physiotherapy.[9, 10, 32, 44, 45, 64-66] At the beginning of this century, the first trials were designed to detect the treatment effect of acromioplasty itself by introducing a surgical "placebo" treatment arm as control group.[36, 52] These trials did also not confirm the success of acromioplasty 2.5 years after surgery, which put the effectiveness of anterior acromioplasty into question. The findings led to alternative hypotheses regarding the aetiology of shoulder complaints and alternative diagnostic definitions of "subacromial impingement syndrome".[22, 24] Since impingement syndrome as such suggested a specific anatomic cause (i.e. subacromial attrition) for pain, the Dutch Orthopaedic Association changed the entity "subacromial impingement syndrome" to a more general term: the "subacromial pain syndrome".[29, 91]

Many intrinsic and extrinsic mechanisms have been proposed to cause subacromial pain.[3, 22, 24, 89] Long before the impingement theory was popularised, Codman already hypothesised in his classic paper of 1931, on both tendon degeneration (i.e. intrinsic mechanism) as well as anatomic variants (i.e. extrinsic mechanism) causing shoulder pain and ultimately a rotator cuff tear.[18] Later, more intrinsic mechanisms have been suggested to cause subacromial pain syndrome including: a subacromial inflammatory reaction with tendon thickening and overuse causing repetitive microtrauma.[3, 22, 24, 89] Many researchers have focused on extrinsic mechanisms causing friction of the tendon under the acromion by a reduction of the subacromial space.[3, 22, 24, 89] This reduction of subacromial volume might be caused by the os acromiale, coracoid, the coracoacromial ligament, acromioclavicular osteophytes and a hooked acromial shape.[3, 22, 24, 89] Lastly, a dynamic reduction of the subacromial space as a result of muscle weakness, causing glenohumeral instability with subsequent dynamic cranialization of the humerus under the acromion, or disturbed scapulothoracic motion (i.e. scapular dyskinesis) have been suggested to cause secondary impingement.[3, 22, 24, 89]

Pathophysiology of the subacromial pain syndrome was studied in the SISTIM project, which started in 2009. The SISTIM project aimed to identify causal mechanisms and to classify patients based on distinct pathophysiological subgroups.[24] This SISTIM project was conducted at the department of Orthopaedics and Rehabilitation from the Leiden University Medical Centre which harbours the laboratory for Kinematics and Neuromechanics. This laboratory has a long-standing track-record in studying the biomechanics and kinematics of the shoulder in a network with the Delft University of Technology and associated hospitals (Medical Centre Haaglanden, the Hague; Alrijne Hospital, Leiderdorp).[1, 2, 19, 20, 23, 25, 26, 53, 54, 80, 81, 85, 86, 112-115]

BIOMECHANICS AND KINEMATICS OF THE SHOULDER

Shoulder Biomechanics

Observations from anatomic dissection resulted in papers describing the assumed mechanics of the shoulder function.[13-15, 39] Movements of the shoulder-girdle were explained by close observations of the anatomic orientation and attachments of shoulder muscles relative to the joint.[13-15, 39] The findings in these anatomic specimens were linked to the observations in-vivo .[13, 15] The application of electromyography and radiographs in patients enabled a better understanding of the complex in-vivo interplay of the shoulder girdle structures. The introduction of radiographs illustrated that abduction was not solely initiated via glenohumeral motion when raising the arm from vertical to the horizontal, but involved movement of the scapulothoracic joint at the beginning of abduction.[35, 58, 74] Electromyographic studies revealed the activity of muscles during shoulder movement and was described in detail by Inman.[58] In these electromyographic studies, it was concluded that the middle deltoid and supraspinatus were main contributors of the abduction moment, while the infraspinatus, teres minor and subscapular muscles were identified as essential stabilizers to allow elevation and rotation of the arm.[21, 58]

Cadaveric and in-silico shoulder models gave us more insight in the requirements for shoulder motion and biomechanical adaptations that occur in case of a rotator cuff tear.[48, 57, 68, 99, 113, 117, 119-121, 124] Cadaveric models illustrated the stabilizing role of the teres minor, infraspinatus and subscapularis.[46, 48, 73, 110, 117] A supraspinatus tear caused significantly higher forces in the remaining intact rotator cuff[48, 117] and may introduce glenohumeral translations.[28, 96] A decrease in joint reaction force with excessive superior humeral head translations occurred when the tear extended in the subscapularis or infraspinatus muscle in these cadaveric models.[48, 99, 117] In line with these results, inverse dynamic simulations demonstrated comparable findings with an increase in force generated by the infraspinatus and subscapularis in case of a supraspinatus tear.[113]

A better understanding of the glenohumeral centre of rotation resulted in more complex studies on in-vivo biomechanics.[21, 102] Although the centre of rotation was considered to be slightly variable, some authors concluded that the glenohumeral joint functioned as a ball-in socket joint with approximately a fixed centre of rotation in healthy volunteers.[102] Based on this conclusion, a calculation of lever arms and force vectors around the glenohumeral joint was made.[103] Accuracy of these first estimations remained questionable, because analyses of shoulder kinematics were conducted in static biplanar test settings, while motion of the shoulder girdle occurs around three axes. Moreover, three-dimensional motion analysis advanced after defining the glenohumeral centre of rotation. Radiostereometric analysis (RSA) provided a methodology to measure three-dimensional shoulder motion. However, the in-vivo RSA research, although very accurate, has not been taken up widely for the evaluation of non-implant related shoulder research, since tantalum beads have to be inserted in the patient.[56] For that matter, other methods were developed to study shoulder motion, like the electromagnetic tracking device as the Flock-of Birds.[59, 62, 63, 77, 85, 88, 104]

Biomechanics in Subacromial Pain Syndrome

A main focus of biomechanical research in "subacromial impingement syndrome" has been the spatial shape of the subacromial space. Elevating the arm between 30 to 120 degrees of abduction brings the humerus in closer proximity to the acromion reducing subacromial space, which could explain the painful arc sign that is found in patients with subacromial impingement syndrome.[27, 40, 41, 50, 55, 61, 87, 109] However, inconsistent outcomes have been found when comparing the subacromial space in patient with subacromial impingement syndrome with asymptomatic controls. Whether the subacromial space width is reduced[28, 37, 50], not different [61, 109], or increased[23, 27] remains unclear. The latter shows the intricate interplay between dynamic cranial translation, posture, scapular rotations, elevation angle and muscle contractions on subacromial space width.[27, 28, 47, 55, 61, 76, 96, 107, 109, 111]

Important to note is that subacromial impingement syndrome evolved to subacromial pain syndrome in the Netherlands recent years, parting the attrition theory as dominant pathologic mechanism.[29, 91] In the past, patients with bursitis, tendinopathy and a rotator cuff tear have been considered as one clinical entity according to the stages of Neer's impingement syndrome for many years.[28, 41, 42, 61] The latter caused huge heterogeneity when outcomes were compared among studies, since it is very likely that patients with subacromial pain syndrome demonstrate different biomechanics and kinematics than patients with a full-thickness rotator cuff tear. Consequently, many prior studies are currently not applicable for the patient with subacromial pain syndrome (i.e. thus a patient with an intact rotator cuff).

Shoulder Kinematics

The physical examination is still an important part of diagnosing a patient. A simple observation of active shoulder motion gives us more information about the functional deficits of the patient. Next to range of motion, the clinician generally observes the scapula-humeral rhythm to determine the presence of scapular dyskinesis. The latter will have inter- and intra-observer variability, but is considered to give clinical information on the type of shoulder pathology. The importance of the scapula in shoulder movement has been acknowledged by Codman in 1911, who described a disturbed scapula-humeral rhythm, as a *"sine qua non"* for the diagnosis of a supraspinatus tear.[17]

Scapular dyskinesis is now defined as "any alteration of normal scapular kinematics"[67], but more frequently "asymmetry in scapulothoracic motion" is used in clinical practice and in literature.[118] Scapular dyskinesis, with an increase in internal rotation, a decrease in lateral rotation (i.e. also known as upward rotation) and posterior tilt are postulated to reduce the subacromial volume by bringing the humeral head in closer contact with the acromion.[34, 75, 111] Whether these observed kinematic alterations are a result of the pathophysiology of disease or a compensatory mechanism, is still part of debate.[67] Interestingly, a comparable prevalence of scapular dyskinesis in healthy volunteers and in patients with subacromial pain was found using clinicians' visual inspection.[101] This indicates a need for more robust quantitative methods to measure the direction and amplitude of small deviations of normal kinematics, like three-dimensional motion analyses. Therefore, glenohumeral and scapulothoracic kinematics have been evaluated by applying radiography, magnetic resonance imaging, opto-electronic systems or electromagnetic tracking systems.[28, 41, 79, 84, 95, 96, 99, 105, 108, 117, 126]

Patients with a rotator cuff tear were found to have reduced glenohumeral elevation and increased scapulothoracic lateral rotation to reach positions above shoulder level, thus confirming Codman's observation in 1911.[28, 84, 96, 105] Most studies had the limitation that kinematics of the shoulder had been calculated at a static elevation angle hampering the validity of these data by allowing a setting phase for the scapula.[28, 42, 95, 96] Pain was an important confounder contributing to a disturbed scapula-humeral rhythm in these patients if comparing them with healthy volunteers. The use of a suprascapular nerve block has been proposed to evaluate the effect of the supraspinatus and infraspinatus muscle on shoulder mobility in healthy volunteers by eliminating the effect of pain. Interestingly, a comparable reduction in glenohumeral elevation and increase in scapulothoracic lateral rotation was found in these simulated posterosuperior rotator cuff tears.[83]

Kinematics in Subacromial Pain Syndrome

Three-dimensional kinematic analyses in "subacromial impingement syndrome" gave contradictory outcomes between studies. Some studies found a decrease in scapular lateral rotation[31, 70, 75], while others did not find a difference[51, 69, 71, 78, 84] or even showed an increased lateral rotation.[82] A reduction in posterior tilt was found by several investigators[31, 70, 71, 75, 78] while others did not[51, 84] or even found more posterior tilt.[69, 82] These inconsistent findings are most probably related to the large heterogeneity in study populations caused by a different interpretation of physical tests among clinicians[22], treatment of patients with a different anatomic substrate of pain as one clinical entity (i.e. impingement syndrome)[70, 75, 78, 82] and investigations in highly selected subgroups based on occupation or sport activities.[69, 71, 75] For that matter, available outcomes are not translatable to the patient in the daily orthopaedic clinical practice. Shoulder kinematics in subacromial pain syndrome has to be evaluated in a group of patients with a more similar phenotype with respect to at least age and anatomy (i.e. intact rotator cuff).

In conclusion, extrinsic compression of the acromion is no longer assumed the dominant pathophysiological pathway contributing to subacromial pain. Despite attrition of the rotator cuff under the acromion may be a long-lasting process, the long-term effect of acromioplasty after 10 to 20 years is not investigated in literature. Alternative pathophysiological pathways contributing to the development of subacromial pain syndrome include a dynamic reduction of subacromial structures due to destabilizing muscle forces within the glenohumeral joint or disturbed shoulder kinematics. Therefore, there is a clear need to use biomechanical and kinematical analyses in a well-defined study population with subacromial pain syndrome.

AIMS OF THE THESIS

1) Evaluation of the long-term effects of subacromial decompression surgery on pain, shoulder function and rotator cuff integrity.
2) Evaluation of shoulder muscle activity and kinematics in patients with subacromial pain syndrome.
3) Evaluating the association of rotator cuff tear size and shoulder kinematics.

OUTLINE OF THIS THESIS

The concept of tendon attrition suggests that subacromial decompression will have an effect after many years. In **Chapter 2**, we present a long-term follow-up study of a randomised controlled trial examining the effects of arthroscopic subacromial decompression on pain, shoulder function and rotator cuff integrity 10 years after the operation. In an observational study, the kinematics and coordination of shoulder muscles in patients with subacromial pain syndrome were compared to asymptomatic volunteers **(Chapter 3)**. In **Chapter 4**, the effect of subacromial anaesthetics on scapular dyskinesis is evaluated and we elaborated on the influence of pain. The association between rotator cuff tear size and glenohumeral/scapulothoracic kinematics is investigated in **Chapter 5**. Changed mechanical loads of intact muscles not being part of the rotator cuff tear (i.e. the deltoid and teres minor muscle) were hypothesised to influence muscle atrophy with age. The alterations in mechanical loads in the shoulder in the presence of a rotator cuff tear were indirectly measured by observing changes in muscle volume **(Chapter 6)**. From here we started to investigate the effects of rotator cuff repair on shoulder kinematics (**Chapter 7**). The mid- to long-term clinical outcomes of a teres major or lattisimus dorsi tendon transfer, a salvage procedure in a chronic massive posterosuperior rotator cuff tear, are evaluated in **Chapter 8**. The study outcomes, their clinical implications and the future perspective are discussed (**Chapter 9**). Finally, a summary of findings is provided (**Chapter 10**).

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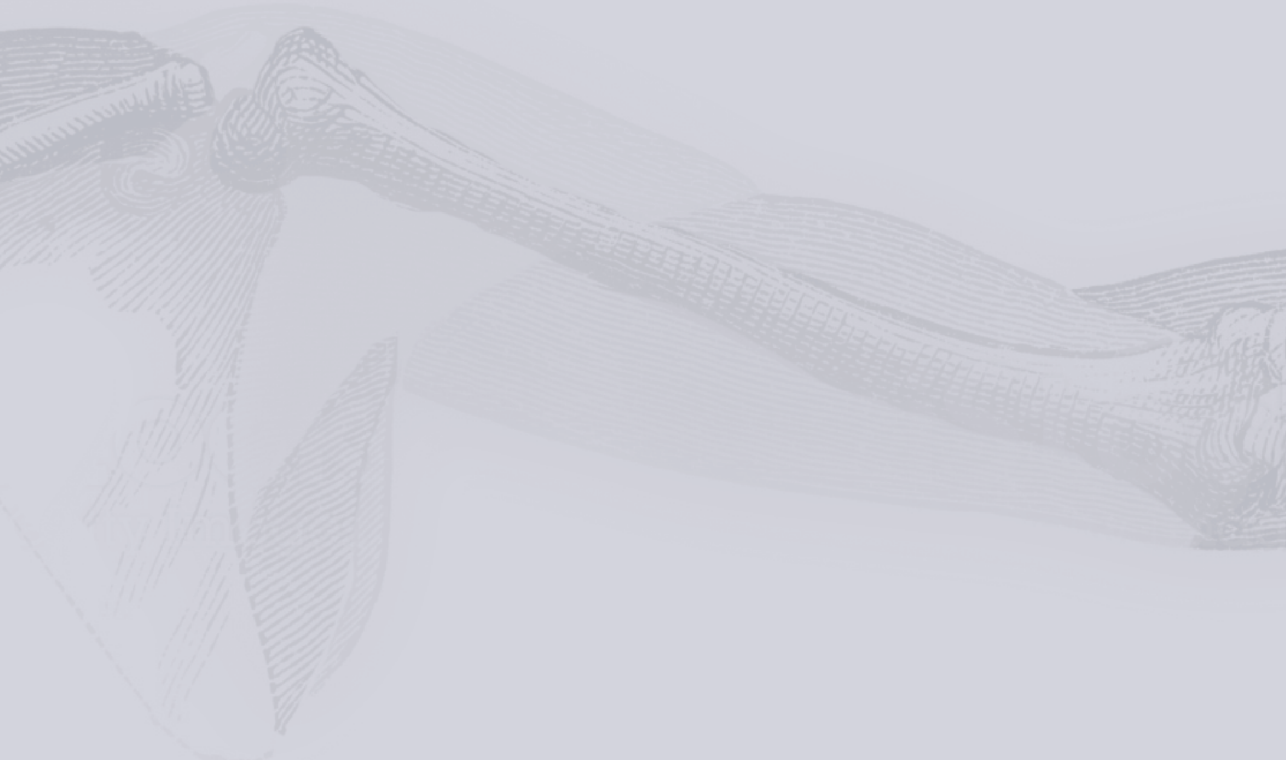

2

Does acromioplasty result in favourable clinical and radiologic outcomes in the management of chronic subacromial pain syndrome?

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ABSTRACT

Background: The treatment effect of acromioplasty for chronic subacromial pain syndrome (SAPS) on long-term shoulder function and rotator cuff deterioration has still to be determined. This study aims to determine the long-term clinical and radiologic treatment effect of arthroscopic acromioplasty in patients with chronic SAPS.

Methods: In this double-blind, randomised clinical trial, 56 patients with chronic subacromial pain syndrome (median age 47 years; range, 31 – 60 years) were randomly allocated to arthroscopic bursectomy alone or to bursectomy combined with acromioplasty and were followed up for a median of 12 years. The primary outcome was the Constant score. Secondary outcomes included the Simple Shoulder Test, Visual Analogue Scales (VAS) for pain, VAS for shoulder functionality, and rotator cuff integrity assessed with Magnetic Resonance Imaging or ultrasound.

Results: A total of 43 patients (77%) were examined at a median of 12 years' follow-up. Intention-to-treat analysis at 12 years' follow-up did not show a significant additional treatment effect of acromioplasty on bursectomy alone in improvement in Constant score (5 points; 95% confidence interval, -5.1 – 15.6), Simple Shoulder Test score, VAS score for pain, or VAS score for shoulder function. The prevalence of rotator cuff tears was not significantly different between the bursectomy group (17%) and acromioplasty group (10%).

Conclusions: There were no relevant additional effects of arthroscopic acromioplasty on bursectomy alone with respect to clinical outcomes and rotator cuff integrity at 12 years' follow-up. These findings bring the effectiveness of acromioplasty into question and may support the idea of a more conservative approach in the initial treatment of SAPS.

INTRODUCTION

Shoulder complaints have a prevalence of up to 48 per 1000 person-years, and each year up to 20% of the adult population has pain in the shoulder.[12, 35] Furthermore, shoulder complaints account for a huge part of health care costs and are a common reason for sick leave from work.[37, 43] The majority of these complaints are primarily attributed to extrinsic compression of the acromion with impingement of the rotator cuff (RC) tendons.[31, 40] As a result of the ongoing debate over the extrinsic compression theory, the "impingement" entity has recently evolved to a more generic term, "subacromial pain" syndrome (SAPS).[9, 10, 36, 40, 42]

Acromioplasty has been the standard treatment for patients having subacromial pain, with over 20.000 procedures per year in New York State, as well as in the United Kingdom.[22, 44] Acromioplasty is considered a successful surgical option in SAPS to reduce mechanical impingement and optimize shoulder function.[22, 31] Various authors have claimed that acromioplasty may prevent the RC from developing a full-thickness tear.[1, 11, 32] Existing randomised controlled clinical trials (RCTs) examining the effect of acromioplasty in SAPS have been pragmatic in nature and focused on the difference between surgery and conservative strategies (e.g. supervised exercise therapy).[4, 5, 13, 14, 24, 25] Thus these study designs have not accounted for the potential impact of bursectomy and placebo effects, resulting in an overestimation of the effect that is attributable to acromioplasty.[2, 17, 18, 21, 31, 33] One prior RCT has taken those effects into account by randomly allocating SAPS patients to bursectomy alone or to bursectomy combined with acromioplasty. No beneficial effects of acromioplasty were shown 2.5 years after surgery.[15] However, the concept of extrinsic compression leading to RC deterioration implies that clinical shoulder symptoms would increase after many years. Consequently, the value of acromioplasty in the treatment of chronic SAPS and prevention of developing RC tears, while broadly applied, has still to be determined.

The aim of this study was to evaluate the long-term clinical effect of arthroscopic acromioplasty with respect to pain, function, and RC integrity in patients with chronic SAPS. For this purpose, we randomly assigned patients with chronic SAPS either to bursectomy alone or to bursectomy in combination with acromioplasty. Because acromioplasty is expected to reduce extrinsic compression with a consequent effect on shoulder related complaints, we hypothesised that acromioplasty improves long-term shoulder function, reduces pain and prevents the development of RC tears in patients with chronic SAPS.

MATERIALS AND METHODS

Study Design and Eligibility Criteria

The research group recruited patients from a previously described prospective, parallel-group, superiority, double-blinded RCT for long-term evaluation.[15] Patients were invited for follow-up between February 2015 and April 2016 at the orthopaedic department of a secondary referral centre (Haaglanden Medical Centre, the Hague, the Netherlands).

At the start of the trial, eligible patients obtained the diagnosis of SAPS by a shoulder orthopaedic surgeon (ERAvA) after assessment of medical history, physical examination, radiographs (anteroposterior view with the humerus in external and internal rotation and trans-scapular view), and direct Magnetic Resonance Arthrography (MRA) of the shoulder. Mandatory clinical signs for inclusion were as follows: pain located in the deltoid region for at least 3 months; inability to lie down on the affected shoulder; pain during abduction, backward flexion or internal rotation; positive Neer or Hawkins impingement test; and a positive lidocaine impingement test. In addition, conservative treatment for at least 6 weeks (i.e. subacromial infiltration, nonsteroidal anti-inflammatory drugs, and supervised exercises) had to be unsuccessful. The exclusion criteria were: calcifying tendinitis, biceps tendinitis, partial- or full-thickness RC tear, labral tear, signs of glenohumeral instability, passive restriction of glenohumeral motion, osteoarthritis of the acromioclavicular or glenohumeral joint, rheumatic diseases, cervical radiculopathy, history of shoulder trauma, synovitis, and prior surgery on the affected shoulder.

The study protocol was approved by the medical ethical research committee "Zuidwest Holland", and registered at the Dutch Trial Register (www.trialregister.nl, Identifier: NTR4723). Each participant gave written informed consent.

Randomisation and Blinding

An independent data manager randomly assigned all eligible patients, just prior to surgery, either to bursectomy alone or to bursectomy plus acromioplasty. Randomisation was performed with 1:1 allocation using a computer-generated random list. Trial participants were blinded for treatment allocation. A blinded independent physician (HEH or AK) clinically assessed each patient. A dedicated musculoskeletal radiologist (WGW), who was uninformed about treatment allocation, performed all radiologic evaluations.

Intervention

Included subjects underwent surgery under general anaesthesia in the lateral decubitus position by an experienced arthroscopic shoulder surgeon (ERAvA).[15] Three standard arthroscopic shoulder portals were created: a posterior portal, a lateral portal, and an anterior portal through the RC interval. Traction was applied to assess the subacromial space. The subacromial space and glenohumeral joint were inspected to rule out alternative diagnoses. All arthroscopic findings were uniformly recorded. First, the subacromial bursa was debrided with a motorized shaver or an electrocautery probe (OPES; Arthrex, Naples, Florida, USA). When the patient was allocated to the acromioplasty group, a motorized burr was used to conduct a partial resection of the anteroinferior surface of the acromion and the distal coracoacromial ligament through the lateral and posterior portals until a flat surface was created.[15] Postoperatively, patients were allowed to use any painkillers when necessary. All patients started a standardized rehabilitation protocol under supervision of a physiotherapist.

Data collection and Outcome Measures

Patients were evaluated at standardized follow-up visits at baseline and 1.5, 3, 6, 12, 24 months or 4 years after surgery, as previously reported.[15] Of the 80 consecutive patients initially screened for eligibility, 23 patients were excluded because of the exclusion criteria on preoperative MRA or during arthroscopy (Figure 1).[15] In addition, one patient died of lung cancer during follow-up and was excluded from the previous study, leaving 56 participants.[15] These 56 subjects were the source population for the present study. For this study, we invited all initially included patients for a clinical and radiologic follow-up evaluation in 2015 or 2016 (median follow-up 12 years, range 9 – 14 years). Of the 56 patients, 13 patients were lost to follow-up (Figure 1). Long-term clinical data were obtained in 43 patients (77%) and 39 subjects (70%) underwent radiologic evaluation.

The primary outcome measure was shoulder function, expressed with the Constant score (CS).[8] Secondary outcome measures were the Simple Shoulder Test (SST), a Visual Analogue Scale (VAS) for pain (from 0 to 100mm, with 100mm indicating severe pain), and a VAS for shoulder functionality (from 0 to 100mm, with 100mm indicating severely impaired shoulder function).[41] The SST score was interpreted as a percentage from 0% to 100%, with 100% representing optimal shoulder function. All patients were asked to score their overall satisfaction, amount of pain reduction, improvement of shoulder function, and whether they would recommend this type of surgery to another patient by use of the following 7-point Likert scale: completely agrees, 0; agrees, 1; partly agrees, 2; neutral, 3; partly disagrees, 4; disagrees, 5; and completely disagrees, 6. Subsequently, a score of 0, 1 or 2 on any of these subjective measures (i.e. satisfaction, pain reduction, improvement in shoulder function and recommendations to another patient) was considered a good or excellent outcome.

Baseline acromial morphology was scored by the orthopaedic surgeon with the combination of standard radiographs, MRA and intra-operative findings because variability for the identification of acromial morphology has been reported with radiographs or MRA alone.[3, 29] At follow-up, the RC was evaluated to investigate the presence of long-term deterioration and RC tears using MRA (Aera, Avanto, or Symphony 1.5-T magnetic resonance imaging unit; Siemens, Erlangen, Germany). Standard shoulder MRI protocols were used to create 3- to 4-mm-thick T2 fat saturation and T1 or proton density slices in multiple orthogonal directions. Images were evaluated by a dedicated musculoskeletal radiologist in a standardized manner regarding the presence of tendinosis, a partial-thickness RC tear, a labral tear, acromioclavicular osteoarthritis, and a full-thickness RC tear. In case of a contraindication for MRI or when an intra-articular injection was refused (n=8), ultrasonography by a musculoskeletal radiologist was used.

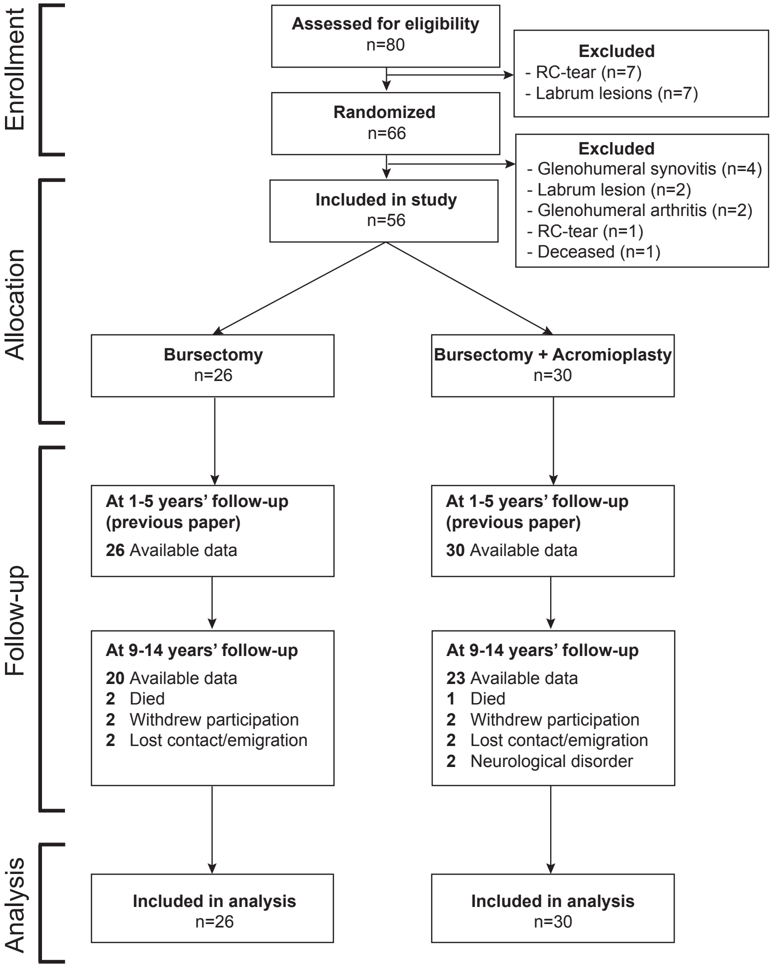

Figure 1. Flow diagram of enrolment, allocation, follow-up and analyses of patients participating in this randomized controlled clinical trial. Abbreviations: RC, rotator cuff.

Statistical analysis

A sample size calculation was performed before the long-term follow-up study was scheduled, with the CS as our primary outcome. We defined a difference of 20 points as clinically important. We assumed a standard deviation of 19 points based on previous work.[15] Therefore, at least 40 participants (20 for each group) were required to detect a statistically significant difference with a power of 90% and a two-sided α of 0.05. The Wilcoxon signed rank test was applied to compare baseline and follow-up continuous outcome data between groups. The prevalence of RC tears in both groups was compared using Fisher's exact test. Generalized estimating equations (GEE) were applied to compare the effect of treatment in both groups on clinical outcomes using (1) an intention-to-treat (ITT), and (2) an as-treated approach. GEE make use of all cases (independent from the presence of missing data), deal with the repeated measures design, and account for potential nonparametric distribution in the outcome.

In our primary analysis, we examined the eventual additional effect of acromioplasty on bursectomy alone at 12 years' follow-up. GEE models were constructed with follow-up time (i.e. baseline, 1.5, 3, 6, 12 and 24 months, 4 years and 12 years) as the repeated factor. Covariance was modelled using an autoregressive structure of order 1. Follow-up time, follow-up time × treatment group (i.e. bursectomy versus bursectomy plus acromioplasty), baseline score, age, sex and shape of acromion (i.e. type I, II, or III according to Bigliani[1]) were included as fixed effects. A second analysis was conducted to evaluate the average effect of acromioplasty over the full follow-up period.

The effect of missing data was evaluated using multiple imputation. Fifty datasets with randomly imputed values were created. Analyses were conducted under the assumption that observed values were able to predict missing values (i.e. missing at random [MAR]). Age, sex, group, reoperation, acromial shape, hand dominance, and available outcome data from other evaluations were used to predict missing outcomes. Although this trial was not designed for subgroup analyses, we performed stratified analyses in a group of patients with a type I acromion and in a group with type II or III acromion (type II and III acromion were combined because the number of patients with type III acromion exposed to bursectomy alone was limited) prior to surgery to determine the effect of acromioplasty on the CS. Statistical analyses were conducted using IBM SPSS statistics for Windows (version 20.0, IBM Corp, 2011, Armonk, New York, USA). We considered a two-sided P value of <0.05 statistically significant.

RESULTS

At baseline, participants had a median age of 47 years (interquartile range [IQR] 12 years) with 55% being female (Table 1). Long-term outcomes were evaluated in 43 patients (77%) with a median of 12 years' follow-up (IQR 2 years, range 9 – 14 years). The median follow-up for the complete population (56 patients) was 11 years (IQR 3 years, range 1 – 14 years).

Primary Outcome

At 12 years' follow-up, both treatment groups showed a significant increase in CS (Table 2). Acromioplasty led to a slightly greater improvement in CS (difference of 5 points; 95% confidence interval [CI], -5 – 15.6 points, P = 0.32) in the intention-to-treat analysis, but this difference did not reach statistical significance. However, the estimated treatment effect of acromioplasty was not statistically significantly different and its CIs excluded the minimal clinically important difference (MCID) (Table 3). The average effect of acromioplasty

Table 1. Baseline characteristics[15]

	Bursectomy n= 26	Bursectomy & Acromioplasty n= 30
Age, median (IQR), yrs.	44 (13)	50 (9)
Follow-up, median (IQR), yrs.	11 (4)	11 (4)
Male sex, n	9 (35%)	16 (53%)
Preoperative symptoms >1yr, n	17 (65%)	26 (87%)
Involved side: right, n	14 (54%)	13 (43%)
Hand dominance: right, n	23 (89%)	26 (87%)
Duration of surgery, median (IQR), min.	33 (21)	39 (10)
Acromion, n		
Type I	11 (42%)	5 (17%)
Type II	13 (50%)	19 (63%)
Type III	2 (8%)	6 (20%)

Abbreviations: IQR, interquartile range; yrs., years; n = number; min, minutes.

including all follow-up evaluations was also not statistically significantly different between both groups. Data obtained from multiple imputation resulted in comparable estimates (Table 3, Figure 2). Subgroup analyses revealed that the effect of acromioplasty on the CS at 12 years' follow-up was 8 points (95% CI, -5.0 – 20.7 points, P = 0.23) in subjects with a type II or III acromion and 0 points (95% CI, -19.9 – 19.4 points, P = 0.98) in patients with a type I acromion.

Secondary Outcome

We did not demonstrate statistically significant differences in any of the secondary outcome measures at 12 years' follow-up. The average effect of acromioplasty using all follow-up evaluations was not statistically significantly different for the SST and VAS for pain in our analysis using raw data. However, after multiple imputation, we found lower VAS scores for pain scores in the acromioplasty group over the entire follow-up (Table 3). A greater improvement in VAS scores for shoulder functionality of 12 mm (95% CI, -1.6 – 22.6) was found after acromioplasty, with a little effect of data imputation (Table 3).

The prevalence of RC tendinitis, bursal-side RC tears, and full-thickness RC tears was comparable between both treatment groups at 12 years' follow-up (Table 2).

Revision surgery was performed in 11 patients (out of 56 subjects). In the bursectomy group, 6 patients were re-operated, of whom 3 within the first postoperative year: Two underwent an acromioplasty, and one underwent a resection of the distal clavicle, and subsequently an RC repair. Three other patients (at 2, 11 and 12 years postoperatively) were scheduled to undergo RC repair, but in one patient no RC tear was found during surgery. In the acromioplasty group, 5 patients were re-operated, of whom 3 did so within the first post-

Table 2. Clinical and radiologic findings at baseline and follow-up

	Bursectomy			**Bursectomy & acromioplasty**		
	Baseline	*9-14 yrs.*	*P value*	*Baseline*	*9-14 yrs.*	*P value*
Clinical evaluation						
N. of patients	26	20		30	23	
Constant Score [a], points	59 (26)	81 (24)	<0.001[*†]	62 (21)	91 (23)	<0.001[*†]
SST [a], %	42 (52)	67 (46)	0.003[*†]	38 (50)	83 (50)	<0.001[*†]
VAS for pain [a], mm	70 (23)	7 (33)	0.004[*†]	70 (30)	4 (19)	<0.001[*†]
VAS for functionality [a], mm	70 (33)	10 (55)	0.001[*†]	65 (20)	4 (23)	<0.001[*†]
Satisfied, n (%)		14 (70%)			18 (78%)	
Improved pain, n (%)		15 (75%)			20 (83%)	
Improved shoulder function, n (%)		15 (75%)			19 (85%)	
Would recommend surgery, n (%)		13 (65%)			19 (83%)	
Radiologic evaluation						
N. of patients		18			21	N.S.[‡]
Acromioclavicular OA, n (%)		8 (44%)			12 (57%)	N.S.[‡]
Articular partial RC tear, n (%)		2 (11%)			1 (5%)	N.S.[‡]
Bursal partial RC tear, n (%)		0 (0%)			1 (5%)	N.S.[‡]
Tendinosis, n (%)		5 (28%)			6 (29%)	N.S.[‡]
Full-thickness RC tear, n (%)		3 (17%)			2 (10%)	N.S.[‡]

Abbreviations: yrs., years; n, number; SST, Simple Shoulder Test; VAS, visual analogue scale; mm, millimetre; N.S., not significant; OA, osteoarthritis; RC, rotator cuff.

[a] Median (IQR)

[*] Statistically significant

[†] Wilcoxon signed rank tests.

[‡] Fishers' exact test.

operative year: One patient underwent a more extensive acromioplasty, and two patients underwent a resection of the distal clavicle. Furthermore, a labral defect was treated after 2 years in one patient, and one patient underwent an RC repair after 11 years.

DISCUSSION

This clinical trial aimed to investigate whether an arthroscopic bursectomy followed by an acromioplasty provides greater long-term improvement in shoulder function or pain relief than does bursectomy alone in patients with chronic SAPS. At 12 years' follow-up, no statistically significant additional effect of acromioplasty on bursectomy alone was found with respect to improved shoulder function or pain reduction. Similarly, the additional effect of acromioplasty on bursectomy alone for the overall follow-up period was not statistically significant for the primary outcome. Moreover, the number of RC tears was comparable

Table 3. Effectiveness of acromioplasty

		Mean effect	95% CI	P value
Raw data[†]				
Constant Score, points				
At 12 years	*ITT*	5	-5.1 – 15.6	0.32
	As-treated	2	-7.9 – 12.8	0.65
Average effect over follow-up	*ITT*	6	-0.7 – 12.5	0.08
	As-treated	5	-1.4 – 11.1	0.13
SST, %				
At 12 years	*ITT*	11	-5.2 – 27.6	0.18
	As-treated	6	-9.2 – 22.2	0.42
Average effect over follow-up	*ITT*	11	-0.0 – 22.0	0.05
	As-treated	8	-2.3 – 19.3	0.12
VAS for pain, mm				
At 12 years	*ITT*	-6	-21.0 – 8.9	0.43
	As-treated	-1	-16.3 – 13.5	0.85
Average effect over follow-up	*ITT*	-7	-17.4 – 3.2	0.18
	As-treated	-5	-14.7 – 4.6	0.31
VAS for functionality, mm				
At 12 years	*ITT*	-15	-31.7 – 2.1	0.09
	As-treated	-3	-19.4 – 13.8	0.74
Average effect over follow-up	*ITT*	-12	-22.6 – -1.6	0.02[*]
	As-treated	-8	-18.2 – 6.3	0.11
Results after multiple imputation[‡]				
Constant Score, points				
At 12 years	*ITT*	4	-4.9 – 12.0	0.41
	As-treated	1	-7.2 – 9.5	0.79
Average effect over follow-up	*ITT*	3	-0.3 – 7.3	0.07
	As-treated	3	-0.6 – 6.7	0.10
SST, %				
At 12 years	*ITT*	5	-7.9 – 18.3	0.43
	As-treated	2	-10.7 – 14.7	0.76
Average effect over follow-up	*ITT*	6	-2.0 – 13.2	0.15
	As-treated	5	-2.9 – 12.1	0.23
VAS for pain, mm				
At 12 years	*ITT*	-6	-16.9 – 5.3	0.31
	As-treated	-2	-13.3 – 9.1	0.71
Average effect over follow-up	*ITT*	-7	-13.5 – -0.6	0.03[*]
	As-treated	-6	-12.5 – -0.3	0.04[*]
VAS for functionality, mm				
At 12 years	*ITT*	-9	-22.2 – 4.5	0.19
	As-treated	0	-13.1 – 13.2	0.99
Average effect over follow-up	*ITT*	-7	-14.4 – 0.0	0.05
	As-treated	-6	-12.6 – 1.6	0.13

Abbreviations: CI, confidence interval; ITT, intention to treat; SST, Simple Shoulder Test; VAS, visual analogue scale; mm, millimetre.

[*] Statistically significant

[†] Generalized estimating equation model with time (i.e. 1.5, 3, 6, 12 and 24 months, 4 years and 12 years), time × group, baseline score, age, sex and shape of acromion were included as fixed effects.

[‡] Generalized estimating equation model with time (i.e. 1.5, 3, 6, 12 and 24 months, 4 years and 12 years), group, baseline score, age, sex and shape of acromion were included as fixed effects.

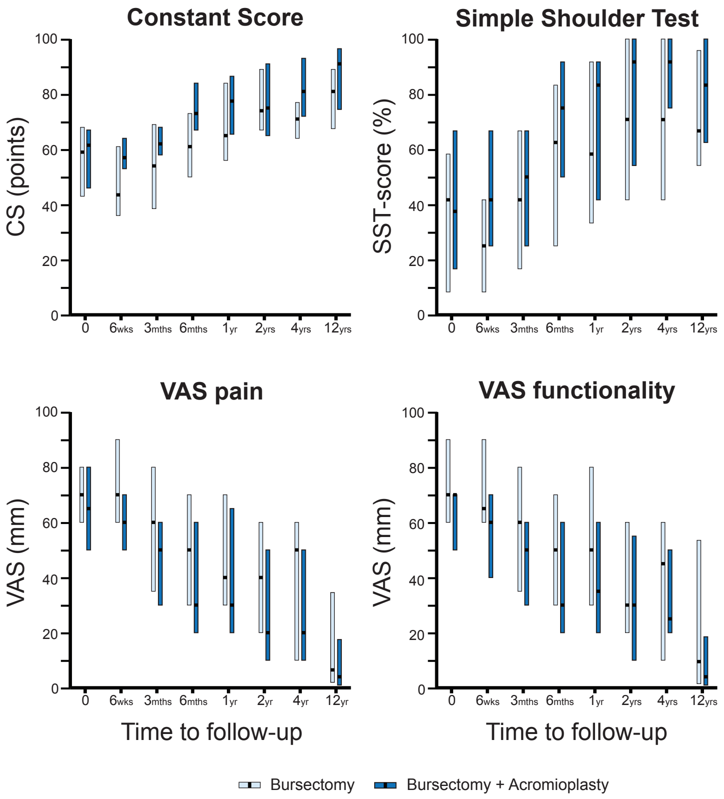

Figure 2. Median and 25th and 75th percentiles of the primary (Constant Score) and secondary outcome measures preoperatively and during follow-up (at 6 weeks, 3 months, 6 months, 1 year, 2 years, 4 years and at a median of 12 years' follow-up). Abbreviations: CS, Constant Score; SST, Simple Shoulder Test; VAS, Visual Analogue Scale.

between both groups, which indicates that acromioplasty does not fully protect RC integrity and RC tears may still develop.

This RCT is the first trial that has investigated the additional long-term effect of acromioplasty on bursectomy alone in the treatment of chronic SAPS. Many previous reports on the effectiveness of acromioplasty in SAPS have been cohort studies.[2, 17, 18, 21, 31, 33] These studies did not account for the natural course of SAPS and the effect of bursectomy on itself. A solitary bursectomy, as conducted in our control group, is sometimes considered a sham procedure, although debridement of the bursa alone has also been reported to improve clinical outcomes.[6] Our randomised design enables us to differentiate between the actual effect of acromioplasty and other effects (e.g. placebo effect or effect of bursectomy). We previously found no beneficial effect of acromioplasty at 2.5 years' follow-up.[15] Consistent with the midterm results, we did not find a significant additional treatment effect of acromioplasty over bursectomy alone on the CS at final follow-up.[15] The average effect over the entire follow-up in our imputed dataset reached statistical significance for VAS scores for pain. However, the CIs of this effect excluded the minimal clinically important difference (MCID) of VAS score for pain (i.e. 14 mm) reported in the literature, which makes its clinical relevance questionable.[39]

The number of full-thickness RC tears found after acromioplasty in our study is in agreement with the prevalence of RC tears in most SAPS cohorts reported in the literature.[2, 20] In 4% to 13% of the patients treated with an acromioplasty, a full-thickness RC tear was found at 15 years' follow-up.[2, 20] On the contrary, Kartus et al reported a percentage of full-thickness RC tears of up to 35% at a mean follow-up of 8.5 years.[23] This high percentage considerably differs from the number of RC tears reported in our study and might be a result of the inclusion of incomplete RC tears (i.e. stage III impingement) at baseline. In the general population, a higher prevalence of RC tears of 35% to 80% has been reported in volunteers aged over 60 years.[30, 45] The higher prevalence of RC tears in the general population might be surprising when considering that the patient with a history of RC complaints has an assumed a higher baseline risk of the development of an RC tear.

An open or arthroscopic acromioplasty is still a widespread therapeutic option after failed conservative management in clinical orthopaedic practice.[22, 34] Although inconsistent results have been reported regarding the optimal surgical technique, the arthroscopic technique allowed us to evaluate the glenohumeral joint and to exclude other intra-articular pathology.[19, 28, 38] Preservation of the deltoid during arthroscopy has been claimed to result in superior function and faster recovery, but consensus on this topic has not been reached yet.[19, 28, 38] As an alternative to surgery, a number of RCTs showed comparable success rates in SAPS after physiotherapy.[4, 5, 13, 14, 16, 24, 25] Shoulder exercises might be more cost-effective than surgery especially as our study suggests that the RC is not protected from tearing after an acromioplasty.[24, 25]

There are some limitations of this study. First, imbalances in the distribution of baseline characteristics existed, although allocation to treatment was random. Therefore, we included several baseline characteristics in our statistical model. Furthermore, the sample size was small. The MCID of the CS was reported after initiation of our study and was shown to be approximately 10 to 11 points.[7, 26] This study was not designed and lacks power to detect these small differences. However, it is questionable whether a larger study would yield different conclusions, because the MCID of the CS reported in literature (e.g. 10 to 11 points) falls just inside the CI of our estimated treatment effect (intension-to-treat analysis raw data; 95% CI: -0.7 to 12.5 points).[26] Similarly, the prevalence of full-thickness tears (10% versus 17%) warrants a larger trial to demonstrate a potential beneficial effect of acromioplasty in preventing the RC from tearing. We do not believe our evaluation of the RC with both ultrasound and MRA has impaired the study because both ultrasound and MRA are accurate modalities for detecting a full-thickness RC tear.[27] Moreover, an RCT is usually not designed to perform subgroup analyses (i.e. based on acromial morphology or coracoacromial morphology) because of limited power. Therefore, our subgroup analyses should be interpreted with care.

Ideally, a future RCT should be performed comparing surgery (i.e. bursectomy with acromioplasty) with a surgical sham procedure in a large sample and subgroup of patients with chronic SAPS to investigate the effectiveness of surgery that could underline or reject our results. Subgroups should involve patients who are more likely to benefit from acromioplasty including patients with a hooked acromion or with fraying of the coracoacromial ligament, because the latter may indicate potential contact of the RC with the coracoacromial arch.

CONCLUSION

Arthroscopic acromioplasty plus a bursectomy does not result in a clinically relevant improvement in shoulder function or relief of pain in patients with SAPS at 12 years' follow-up compared with bursectomy alone. Furthermore, we were unable to prove a statistically significant difference in the prevalence of RC tears between both groups at 12 years' follow-up. These findings bring the effectiveness of acromioplasty for all patients with chronic SAPS into question, and may support the idea of a conservative approach in the initial treatment of SAPS.

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4

Subacromial anaesthetics increase asymmetry of scapular kinematics in patients with subacromial pain syndrome

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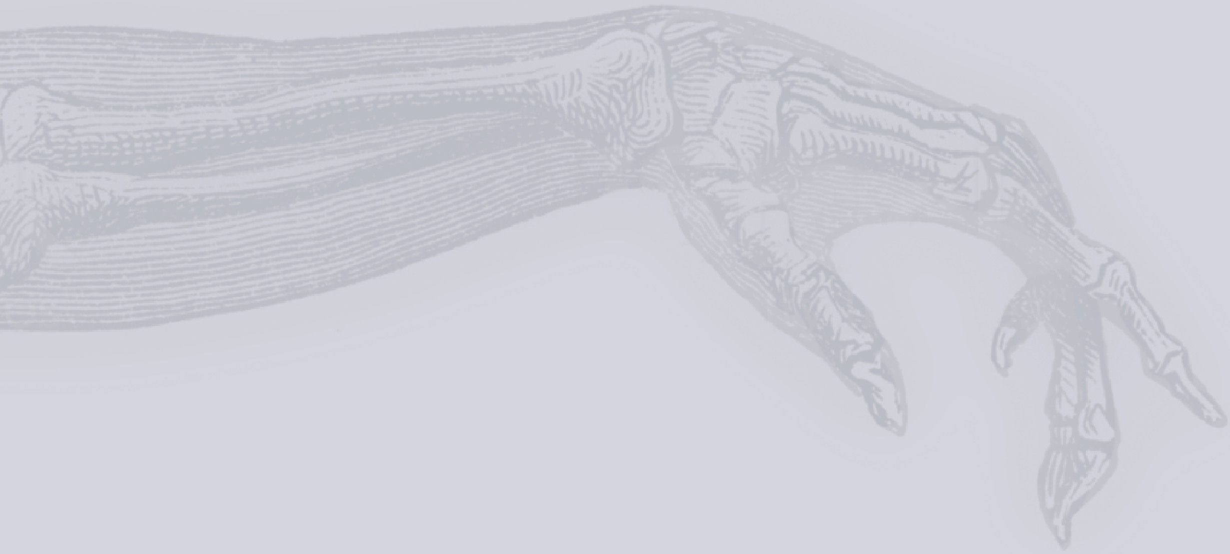

ABSTRACT

Background: Subacromial pain syndrome (SAPS) and scapular dyskinesis are closely associated, but the role of pain is unknown. We hypothesised that pain results in asymmetrical scapular kinematics, and we expected more symmetrical kinematics after infiltration of subacromial anaesthetics. The aim of this study was to investigate the effect of subacromial anaesthetics on scapular kinematics in patients with SAPS.

Methods: In this observational cohort study, we evaluated shoulder kinematics in 34 patients clinically and radiological (magnetic resonance arthrography) identified with unilateral SAPS using three-dimensional electromagnetic motion analysis (Flock of Birds). Scapular internal rotation, lateral rotation and posterior tilt of the affected shoulder were compared with the kinematics of the unaffected shoulder and following subacromial anaesthetics. Additionally, the association of pain (Visual Analogue Scale, VAS) and scapular rotation was analysed.

Results: Compared with the contralateral healthy shoulder, 5° (95% confidence interval 0.4° – 9.7°, P = 0.034) more scapular internal rotation was observed in the affected shoulder at 110-120° of abduction. Following subacromial anaesthetics in the affected shoulder, internal rotation increased (2°, 95% confidence interval 0.5° – 3.9°, P = 0.045) and posterior tilt decreased (3°, 95% confidence interval 1.5° – 5.0°, P = 0.001) at 110-120° of abduction. Less scapular lateral rotation was significantly associated with higher pain scores before infiltration (R = 0.45, P = 0.013).

Conclusions: More scapular internal rotation was observed in affected shoulders of patients with SAPS compared with unaffected shoulders. Subacromial infiltration did not restore kinematics towards symmetrical scapular motion. These findings suggest that subacromial anaesthesia is not an effective means to instantly restore symmetry of shoulder motion.

INTRODUCTION

Subacromial pain syndrome (SAPS), also known as subacromial impingement, is prevalent in patients with shoulder complaints.[7, 36] SAPS is characterised by shoulder pain, decreased muscle strength and impaired active shoulder function.[11] The aetiology of SAPS is debated**,** as multiple factors are advocated to contribute to its pathophysiology.[5, 15, 19] These factors include the compression of anatomic structures within the subacromial space, overuse of glenohumeral muscles, dynamic glenohumeral translation by rotator cuff degeneration and scapular dyskinesis.[5, 6, 11]

Quantitative assessment of scapular kinematics with three-dimensional (3D) electromagnetic tracking revealed scapular dyskinesis in patients with SAPS.[17, 20, 23] Scapular dyskinesis with increased internal rotation (i.e. protraction), decreased lateral rotation (i.e. upward rotation) and posterior tilt are suggested to reduce the subacromial space and to impinge subacromial tissues.[8, 10, 12, 17, 20, 32, 39] The association between altered scapular kinematics and SAPS led to the application of several programmes targeted at scapular movements.[1, 13, 22] Unfortunately, success rates of treatment vary from 24%-69%.[13, 22] The latter underlines the still unclear relation between subacromial shoulder pain and scapular dyskinesis. If scapula dyskinesis, clinically referred to as asymmetry in scapular motion is the consequence of pain, scapular kinematics may return to symmetrical shoulder kinematics after infiltration of subacromial anaesthetics.[35] Ettinger et al. studied the effect of subacromial anaesthetics in shoulders with SAPS related this kinematics to healthy controls, but it remains unknown whether kinematics are more symmetrical after subacromial infiltration with anaesthetics.[9]

The purpose of this study is to observe changes in scapular kinematics after subacromial anaesthetics in patients with SAPS. We hypothesise that scapular kinematics are asymmetric with more internal rotation, less lateral rotation and less posterior tilt in the affected shoulder. Second, we hypothesise that scapular kinematics restore to symmetrical kinematics after infiltration of subacromial anaesthetics in the shoulder with subacromial pain.

MATERIALS AND METHODS

Between April 2010 and December 2012 all consecutive patients referred to the outpatient clinics of three participating hospitals (Leiden University Medical Centre, Medical Centre Haaglanden and Rijnland Hospital) were evaluated for inclusion in this cross-sectional biomechanical cohort study (Trial register no. NTR2283). The study protocol has been previously published.[6] Eligible patients were invited at the (Leiden University medical Centre, Leiden, the Netherlands) for shoulder evaluation by various experimental set-ups including 3D electromagnetic motion analysis. The institutional medical ethical review board approved this study (P09.227) and written informed consent was obtained for every included patient.

Participants

Inclusion of patients was based on clinical symptoms, shoulder X-ray's and magnetic resonance arthrography (MRA). Patients, aged 35-60 years, with unilateral shoulder complaints for at least 3 months due to SAPS were eligible for inclusion. SAPS was considered when a positive Hawkins test, a positive Neer impingement test and at least one of the following symptoms were present: pain during daily life activities with arm abduction, extension, and/or internal rotation, pain at night or incapable of lying on the shoulder, painful arc, diffuse pain at palpation of the greater tuberosity, scapular dyskinesis, and positive full or empty can test or positive Yocum test.[6]

Exclusion criteria were: insufficient language skills, no informed consent, any form of inflammatory arthritis of the shoulder, clinical signs of glenohumeral or acromioclavicular osteoarthritis, history of shoulder surgery, fracture or dislocation of the affected shoulder, cervical radiculopathy, glenohumeral instability, decreased passive function (e.g. frozen shoulder), and presence of a pacemaker or other electronic implants. Additionally, patients were excluded in case of an alternative diagnosis on radiographs or MRA like: calcific tendinitis, full-thickness rotator cuff tear, partial articular supraspinatus tendon avulsion (PASTA lesion), labrum or ligament pathology, pulley lesion, biceps tendinopathy, os acromiale, tumour, cartilage lesion, and a bony cyst. All MRA were evaluated by an independent radiologist.

Initially, 66 patients were identified with SAPS and were subsequently scanned with MRA. From these 66 patients, 32 subjects (Figure 1) were excluded due to an alternative diagnosis on the MRA (32%) or other exclusion criteria (17%), resulting in a total of 34 included patients with SAPS.

Measurement set-up

Three-dimensional motion was measured using the Flock of Birds electromagnetic tracking system (Ascension Technology Inc., Milton, Vermont, USA). The measurement set-up consisted of an extended range transmitter and six sensors to quantity bilateral shoulder motion in six degrees of freedom. The measurement method and analysis were previously described and validated.[3, 14, 24, 26-28]

Patients were seated in a standardized measurement set-up. Five wired receivers were attached using either adhesive tape (thorax and bilateral scapulae) or straps with hook-and-loop fastener (bilateral distal humeral). The thorax sensor was adhered just above the xyphoid process and the scapular sensors were adhered on the flat cranial surface of the acromion. The humeral sensors were secured at the posterior flat surface of the distal upper arm. Additionally, one sensor was attached to a stylus to digitize bony landmarks.

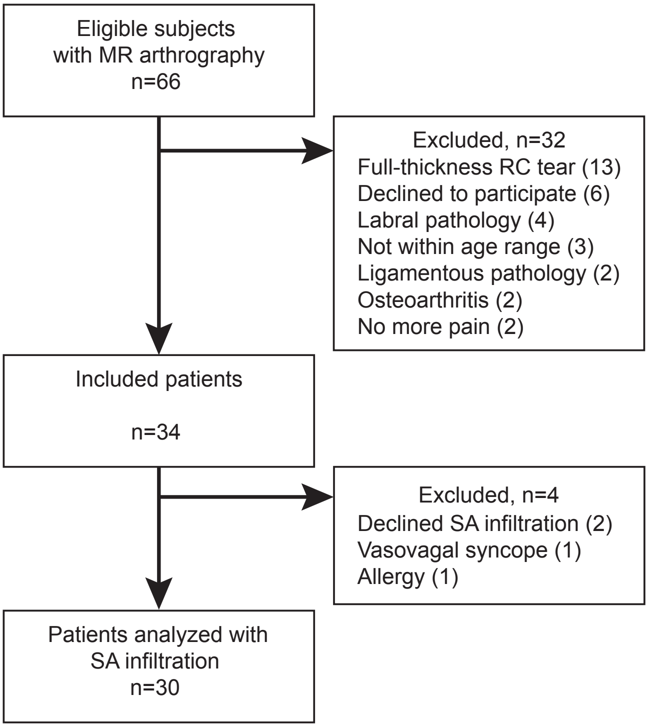

Figure 1. Flow-chart. Abbreviations: n, number; MR, magnetic resonance; RC, rotator cuff; SA, subacromial.

The global and local Cartesian coordinate systems were described in accordance to the recommended ISB protocol.[40] Twenty-four bony landmarks were identified by palpation and were digitized using a stylus to determine a local coordinate system of the bony rigid bodies and its spatial orientation.[3, 24].We used the angulus acromialis for the local coordinate system of the scapula to limit data dispersion and potential gimbal lock in overhead positions.[3] The glenohumeral rotation centre was estimated by a least square method in a linear regression model.[26, 37] Positions and orientations of the sensors were recorded at a sampling rate of approximately 30Hz.

Patients were instructed to bilaterally complete four unconstrained tasks twice to their maximal range of shoulder motion and by keeping the arm in the appropriate plane: (1) elevation in the frontal plane, i.e. referred to as abduction; (2) forward elevation in a parasagittal plane, i.e. referred to as forward flexion; (3) backward elevation in a parasagittal plane, i.e. referred to as extension and (4) external rotation. External rotation was performed in 90^0 of forward flexion and with the elbow 90^0 flexed. Patients were instructed to complete each movement in approximately 10 seconds with a constant velocity. Forward flexion, extension and external rotation were only used to determine the maximal range of motion. For abduction we further investigated the scapulothoracic motion.

Data processing

Positions were expressed in the right-handed local coordinate system of the thorax around perpendicular anterior (X_t), superior (Y_t) and lateral (Z_t) directed axes. Rotations were described using Euler or Cardan angle sequences as recommended.[40] Scapulo-thoracic motion (Y_t-x_s'-z_s") was described as internal rotation (positive rotation around thoracic Y_t-axis and also known as protraction), lateral rotation (negative rotation around scapular x_s'-axis and also known as upward rotation) and posterior tilt (positive rotation around scapular z_s"-axis). Scapular internal rotation, lateral rotation and posterior tilt are here presented as positive motions. Humero-thoracic motion (Y_t-x_h'-y_h") was described as plane of elevation (rotation around thoracic Y_t-axis), elevation (negative rotation around humeral x_h'-axis) and external rotation (negative rotation around humeral y_h"-axis). Humeral elevation and external rotation are presented as positive motions.

Data were analysed by custom made software in MATLAB (2013b release, The MathWorks Inc., Natick, Massachusetts, USA). The scapular positions were calculated for every participant and for every 10° increment from 10°-120° of abduction (eleven intervals). Scapular motion at higher than 120° elevation angles were not included in the analysis since skin movement artefacts at high humeral elevation angles introduce measurement inaccuracies.[3, 14, 25]

Clinical assessment of pain and function

Patients reported their daily experienced pain at rest and movement during activities of daily living on a 100mm Visual Analogue Scale (VAS, 0mm, no pain; 100mm, severe pain). VAS for pain during elevation of the arm was not obtained in one participant. Furthermore, we obtained the Constant Score before the infiltration of subacromial anaesthetics.[2] Patients repeated shoulder abduction approximately 10-20 minutes after the infiltration of 5 ml of 1.0% lidocaine via a 21 gauge needle in the subacromial space using a posterior approach.[21] Following subacromial anaesthetics, all patients verbally reported reduced pain. Sensors were left in place during administration of anaesthetics and bony landmarks were not remeasured after infiltration.

Statistical analysis

Categorical data were described with numbers and percentages. Non-parametric data were described with medians and interquartile ranges (IQR). Normally distributed data were described with means and 95% confidence intervals (CI). Studying the effect of subacromial infiltration was a secondary goal of our SAPS cohort study.[6] We conducted an interim analysis on all 34 consecutive patients included between April 2010 and December 2012, after which we suspended further kinematic experiments after subacromial infiltration.

To compare maximal shoulder movements a paired Student's t-test was used. Scapular kinematics were analysed for abduction by using a linear mixed model analysis.[38] Since two movements within a single subject are related, we calculated the paired difference between: (1) unaffected versus affected shoulder before the application of anaesthetics, and (2) affected shoulder before versus after the infiltration of anaesthetics. The dependent variable was the paired difference in scapulothoracic motion (i.e. scapular internal rotation, lateral rotation and tilt). Abduction intervals were the repeated factor. Since errors between repeated measurements (i.e. intervals) are related (i.e. covariance), covariance at different elevation angles was modelled using an autoregressive structure of order one with unequal variances.[38] The abduction interval was our independent variable of interest. Small variance in humeral rotations may exist when repeating abduction, thought differences in plane of humeral elevation or humeral axial rotation did not change the study outcome and were therefore not incorporated in our final models. The relation between scapular kinematics and VAS for pain during shoulder movement was investigated by forced entry linear regression analysis for each rotation. Statistical analyses were performed using IBM SPSS statistics for Windows (version 20.0, IBM Corp, 2011, Armonk, New York, USA). A two-sided P value of < 0.05 was considered statistically significant.

RESULTS

Thirty-four patients with SAPS were analysed in this study (Table 1). The effect of subacromial infiltration was analysed in 30 patients, because 4 patients were excluded: vasovagal syncope (n=1), known allergy to lidocaine (n=1) and patients' refusal to undergo infiltration (n=2).

Maximal abduction (146° ± 15.4° versus 136° ± 20.0°; mean difference 9°, 95% CI 3.9° – 15.0°, P = 0.002) and forward flexion (145° ± 13.4° versus 138° ± 12.3°; mean difference 6°; 95% CI 2.2° – 10.7°, P = 0.004) were higher for the unaffected shoulder compared with the affected shoulder. Extension (59° ± 10.8° versus 55° ± 12.6°; mean difference 4°; 95% CI -0.2° – 7.4°, P = 0.059) and external rotation in 90^0 of forward flexion (85° ± 10.9° versus 81° ± 13.2°; mean difference 4°; 95% CI -0.4° – 8.5°, P = 0.075) were not significantly higher in the unaffected shoulders.

Following subacromial anaesthetics, only maximal abduction improved in the affected shoulder from 136° ± 20.0° to 141° ± 16.0° (mean difference 5°; 95% CI, 0.1° – 9.8°, P = 0.046).

Table 1. Baseline characteristics

N. of patients	**34**	
Age, mean ± SD, yrs	50 ± 6.2	
Weight, mean ± SD, kg	80 ± 14.4	
Length, mean ± SD, cm	173 ± 11.8	
Female, n (%)	20 (58.8)	
Left side affected, n (%)	20 (58.8)	
Right side dominance, n (%)	29 (85.3)	
Spontaneous onset of symptoms, n (%)	28 (82.4)	
Pain at night, n (%)	29 (85.3)	
Pain during daily life activities, n (%)	29 (85.3)	
Tendinosis supraspinatus, n (%)	20 (58.8)	
Effusion bursa, n (%)	14 (41.2)	
VAS at rest, median 25th and 75th percentile, mm	12	2.0-25.3
VAS during motion, median 25th and 75th percentile, mm	40	17.5-58.0
CS, median 25th and 75th percentile, points	73	69.0-80.3

Abbreviations: n, number; yrs, years; SD, standard deviation; kg, kilograms; cm, centimetre; VAS, visual analogue scale; mm, millimetre; IQR, Interquartile range; CS, Constant Score.

Scapular kinematics in unaffected versus affected shoulders

With humeral abduction, we observed scapular external rotation (Figure 2A), lateral rotation (Figure 2B) and posterior tilt (Figure 2C). The difference in scapular internal rotation was significantly dissimilar (P = 0.020) at various abduction intervals (Table 2). No differences could be detected at the lower arm positions (i.e. < 80° arm abduction), indicating no initial differences. At of 80° of arm abduction, internal rotation was higher in the affected shoulders. For example, scapular internal rotation was 5° (95% CI 0.4° – 9.7°, P = 0.034) higher in the affected shoulder at 110-120°.

Lateral rotation and scapular posterior tilt were comparable between the affected and unaffected shoulders.

Effect of subacromial anaesthetics on scapular kinematics

Following subacromial anaesthetics, the difference in internal rotation was dissimilar (P < 0.001) at various intervals of abduction (Table 3). Posterior tilt also significantly varied (P = 0.013) over the abduction intervals. The increase in scapular internal rotation and decrease in posterior tilt was only apparent at higher abduction angles. For example, the affected shoulder was 2° (95% CI 0.5° – 3.9°, P = 0.045) more internally rotated, and posterior tilt was 3° (95% CI 1.5° – 5.0°, P = 0.001) decreased after subacromial infiltration at 110-120° of abduction (Table 3). Lateral rotation was not affected by subacromial infiltration (P = 0.445). Internal rotation, lateral rotation and posterior tilt were not different between the two abduction movements in the unaffected shoulder.

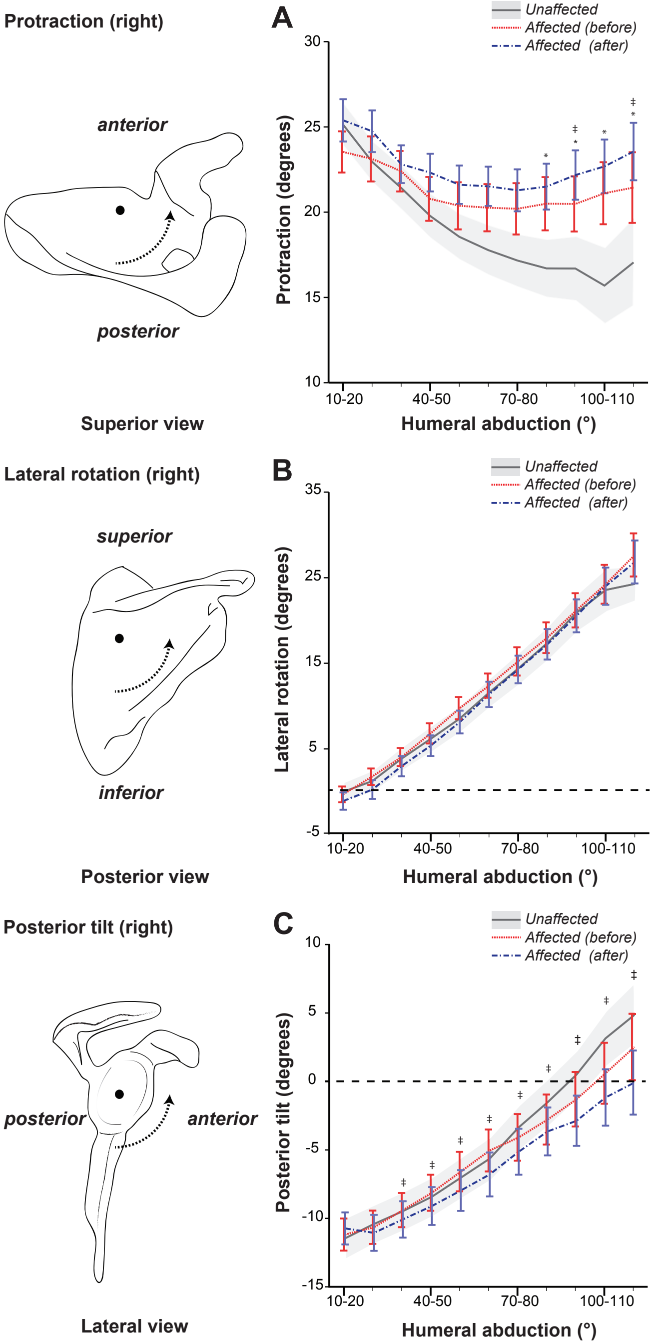

Figure 2. Scapular kinematics as function of abduction. Data are presented as means, and bars represent one standard error. The data were analysed with a *pair-wise* linear mixed model analysis.

[*] Statistically significant differences between the unaffected versus affected shoulder before infiltration.

[‡] Statistically significant differences between the affected shoulder before infiltration versus after infiltration of analgesics.

Table 2. Mixed model analysis for scapular motion

Scapular internal rotation				
		Unaffected – affected (before infiltration)		
	Model	*Mean change*	*95% CI*	*P value*
10-20°	0.020*	0	-2.7 – 3.6	0.779
20-30°		-0	-3.1 – 2.9	0.937
30-40°		-1	-3.7 – 1.9	0.506
40-50°		-1	-3.9 – 2.0	0.509
50-60°		-2	-4.7 – 1.2	0.230
60-70°		-3	-5.5 – 0.6	0.107
70-80°		-3	-6.2 – 0.2	0.065
80-90°		-4	-7.3 – -0.4	0.028*
90-100°		-4	-7.9 – -0.2	0.041*
100-110°		-5	-8.9 – -0.4	0.034*
110-120°		-5	-9.7 – -0.4	0.034*
Scapular lateral rotation				
10-20°	0.898	-0	-2.9 – 2.8	0.781
20-30°		-1	-3.5 – 2.5	0.891
30-40°		-0	-3.3 – 3.1	0.865
40-50°		-1	-3.8 – 2.7	0.673
50-60°		-1	-4.5 – 2.2	0.581
60-70°		-1	-4.0 – 2.4	0.603
70-80°		-1	-4.2 – 2.4	0.499
80-90°		-1	-3.9– 2.6	0.727
90-100°		-0	-3.9 – 3.3	0.952
100-110°		-0	-4.0 – 3.5	0.752
110-120°		-1	-4.4 – 3.3	0.964
Scapular posterior tilt				
10-20°	0.248	0	-1.8 – 2.7	0.692
20-30°		0	-2.2 – 2.3	0.982
30-40°		-0	-2.4 – 1.8	0.778
40-50°		-1	-2.7 – 1.7	0.655
50-60°		-1	-3.0 – 1.8	0.608
60-70°		-1	-3.2 – 2.0	0.646
70-80°		0	-2.8 – 2.9	0.954
80-90°		1	-2.6 – 3.7	0.724
90-100°		1	-2.5 – 4.6	0.545
100-110°		1	-2.6 – 5.4	0.486
110-120°		2	-2.6 – 6.2	0.413

Mean differences between the unaffected and affected shoulder (before subacromial infiltration) at the lowest (10° to 20°) and highest (110° to 120°) abduction interval. Differences appeared at higher degrees of humeral abduction and no offset differences were observed. Abbreviations: CI, confidence interval.

* statistically significant.

Table 3. Mixed model analysis for scapular motion

Scapular internal rotation				
		Affected (before) – Affected (after infiltration)		
	Model	*Mean change*	*95% CI*	*P value*
10-20°	<0.001*	-1	-2.8 – 0.2	0.085
20-30°		-2	-3.1 – 0.1	0.072
30-40°		-0	-2.0 – 1.5	0.797
40-50°		-1	-2.9 – 0.1	0.074
50-60°		-1	-2.5 – 0.5	0.175
60-70°		-1	-2.2 – 0.3	0.114
70-80°		-1	-2.1 – 0.3	0.148
80-90°		-1	-2.3 – 0.5	0.205
90-100°		-2	-3.2 – -0.3	0.017*
100-110°		-2	-3.1 – 0.0	0.055
110-120°		-2	-3.9 – -0.5	0.045*
Scapular lateral rotation				
10-20°	0.445	1	-0.3 – 1.7	0.181
20-30°		1	0.1 – 2.4	0.031*
30-40°		1	-0.1 – 2.1	0.070
40-50°		1	-0.2 – 2.7	0.077
50-60°		1	-0.1 – 2.8	0.065
60-70°		1	-0.8 – 2.3	0.334
70-80°		1	-1.0 – 2.4	0.426
80-90°		0	-1.5 – 2.4	0.653
90-100°		0	-1.8 – 2.1	0.869
100-110°		-0	-2.5 – 2.2	0.885
110-120°		-0	-3.0 – 2.2	0.761
Scapular posterior tilt				
10-20°	0.013*	0	-0.9 – 1.5	0.559
20-30°		1	-0.4 – 2.0	0.171
30-40°		1	0.1– 2.4	0.040*
40-50°		1	0.2 – 2.6	0.020*
50-60°		2	0.5 – 2.9	0.009*
60-70°		2	0.6 – 3.2	0.005*
70-80°		2	0.4 – 3.2	0.013*
80-90°		2	0.3 – 3.0	0.022*
90-100°		2	0.3 – 3.5	0.022*
100-110°		2	0.6 – 4.0	0.010*
110-120°		3	1.5 – 5.0	0.001*

Mean differences between the affected shoulder before versus after subacromial infiltration at the lowest (10° to 20°) and highest (110° to 120°) abduction interval. Differences appeared at higher degrees of humeral abduction and no offset differences were observed. Abbreviations: CI, confidence interval.

* statistically significant.

Association between scapular kinematics and VAS for pain

Median VAS for pain at rest was 12 mm (IQR 2 – 25mm) and movement during activities of daily living 40 mm (IQR 18 – 58mm). Reduced lateral rotation at the initial abduction interval was significantly associated with a higher VAS for pain (2°/mm VAS) in the affected shoulder before infiltration was applied (Table 4).

Table 4. Association between pain and scapular kinematics in the affected shoulder

Abduction	R		Mean change	95% CI			P value
10-20°	0.036	Internal rotation	−0	-1.7	–	1.4	0.852
	0.456	Lateral rotation	−2	-3.8	–	-0.5	0.013*
	0.363	Posterior tilt	−1	-2.8	–	0.0	0.053

Results of forced entry linear regression analysis for the prediction of VAS for pain during elevation of the arm in the affected shoulder at the lowest interval (10-20°). The change in scapular rotation on the VAS pain scale is reported in °/mm. Abbreviations: R, correlation coefficient; CI, confidence interval.

* statistically significant.

DISCUSSION

Scapular kinematics were studied before and after infiltration of the subacromial space with anaesthetics in the affected shoulder. There was more scapular internal rotation at higher abduction angles in the affected shoulder compared with the contralateral unaffected shoulder. Following subacromial anaesthetics, scapular kinematics did not restore to symmetric scapular kinematics and a further increase in internal rotation and a further decrease in posterior tilt was observed.

Our findings on the effect of subacromial anaesthetics largely agree with the results of a previous study.[9] Following the infiltration of subacromial anaesthetics, the authors reported a comparable reduction in posterior tilt at greater elevation angles in shoulders of patients.[9] Ettinger et al. did not observe an effect of infiltration on internal rotation, which is in contrast to our findings.[9] In contrast to the healthy controls used in the study of Ettinger et al., we investigated the effect of subacromial anaesthetics compared to the contralateral asymptomatic shoulder, because scapular dyskinesis was previously defined as asymmetrical scapular kinematics. Participants from both studies elevated their arm in a different plane (i.e. elevation in the scapular plane versus frontal plane), which makes a direct comparison less appropriate. Scapular kinematics in the scapular plane are different from kinematics in the frontal plane.[18] Although SAPS is frequently identified after physical examination, physical examinations lack accuracy to discriminate SAPS from a full-thickness RC tear and clinicians disagree on diagnostic criteria for SAPS.[5, 30] Dissimilar inclusion criteria may result in different samples of patients with SAPS and may influence study outcomes. In this study patients were included after excluding patients with a rotator cuff tear or other intra-articular pathology found on MRA. Additional imaging improved homogeneity of the study population. Inclusion of rotator cuff tears might have biased our study due to the pathologic lateral rotation observed in patients with a rotator cuff tear.[16, 31] Lidocaine will diffuse to the glenohumeral joint in patients with a rotator cuff tear, and therefore may obscure the effect of subacromial anaesthetics in patients with SAPS.

Contradicting results have been reported with respect to (pathologic) scapular kinematic patterns in patients with SAPS.[8, 12, 17, 20, 23] In concordance with most literature, we found less posterior tilt in the affected shoulder.[9, 12, 17, 20, 23] There is no consensus in literature on how internal rotation or lateral rotation in patients with SAPS differs from kinematics in healthy shoulders.[8, 17, 20, 23] Some authors demonstrated reduced lateral rotation in SAPS, while others did not or even found increased lateral rotation.[8, 17, 20, 23] Different selection criteria, measurement set-up or data processing (e.g. planes of elevation, bony landmarks, rotation sequences) may partially explain inconsistencies. Nevertheless, many authors postulate that increased internal rotation, reduced lateral rotation and posterior tilt may result in a decline of the anterior subacromial space with subsequent painful compression of subacromial tissues.[8, 12, 17, 20, 32] The possibility that an inverse relation, where subacromial pain creates asymmetry of scapular motion, should however not be ignored a priory.

Subacromial anaesthetics have the ability to reduce pain and pathologic antagonistic muscle activity of shoulder adductors when abducting the humerus.[4, 33] Subsequently, we hypothesised that pain results in scapular dyskinesis with a comparable restoring effect of lidocaine on scapular dyskinesis. However, we did not find symmetrical scapular kinematics after subacromial anaesthesia, which does not support our hypothesis. Further, this finding may indicate that subacromial infiltration alone is not sufficient to restore scapular kinematics in patients with SAPS and might support the use of specific exercise strategies targeting scapular kinematics and scapular stabilization.[13] However, the response on lidocaine infiltration must be interpreted with caution. Lidocaine infiltration may inhibit proprioceptive or other receptors within the shoulder, although no effect of subacromial anaesthetics on position sense was reported in participants without shoulder complaints.[42] Next, muscle activation might gradually change over time after infiltration, though it is currently unknown how motor output is exactly affected by a sudden relieve of pain.[34] Moreover, the infiltrated volume may increase subacromial pressure which may increase asymmetry of scapular motion found in our study.

This study has several methodological limitations. Although 3D electromagnetic motion analysis is a valid way to assess shoulder motion, the estimation of the glenohumeral rotation centre and artefacts derived from friction between skin and bone potentially introduce measurement variability.[3, 14, 25, 26] In addition, different velocities between repeated movements may have an effect on the outcome. Previous research demonstrated that asymptomatic rotator cuff tears are prevalent, especially in patients with contralateral shoulder complaints.[29, 41] Asymptomatic pathology in the contralateral shoulder could limit the power to detect asymmetry in scapular motion. In addition, the effect of subacromial anaesthesia on pain may have been incomplete by the limited accuracy of the infiltration technique.[21] The effect of subacromial infiltration was not quantitatively assessed on a VAS for pain scale during shoulder movement, although verbal feedback was obtained. Incomplete anaesthesia will lead to an increase in variance within the dependent variable and thus a lower chance to detect an effect on kinematics. Finally, an healthy control group is warranted to evaluate whether observed effects of subacromial anaesthetics in SAPS are exclusively attributed to the elimination of pain.

Future research may elucidate the definitions of pathologic scapular kinematics, evaluate the effect of subacromial anaesthetics in healthy controls and examine the natural course of scapular dyskinesis in patients with SAPS.

CONCLUSION

The affected shoulder in patients with SAPS had more scapular internal rotation compared with the contralateral unaffected shoulder. Less lateral rotation and posterior tilt were associated with higher patient-reported pain. Scapular kinematics did not instantly restore symmetry of shoulder kinematics after the infiltration of subacromial anaesthetics, but we even observed an increase in asymmetrical scapular motion. These findings indicate that subacromial infiltration with lidocaine may not be an effective means for short-term return to symmetrical shoulder motion.

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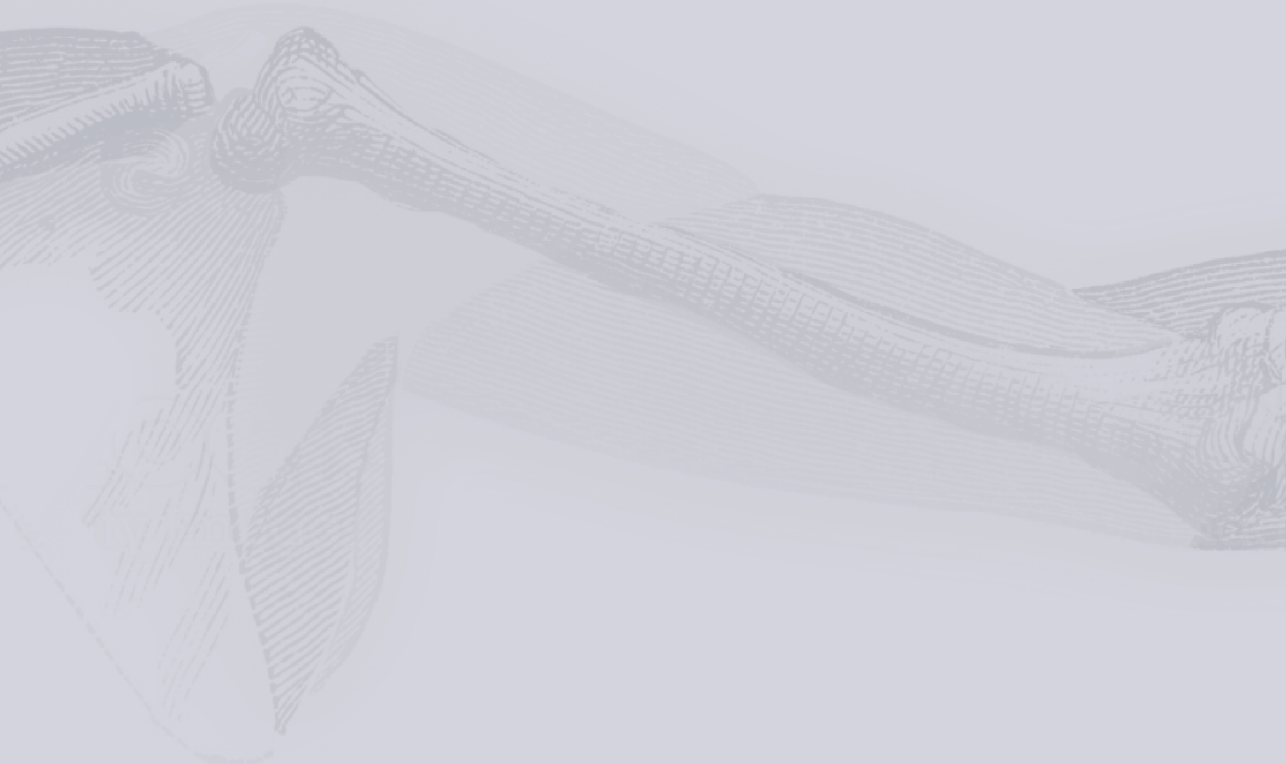

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The effect of a rotator cuff tear and its size on three-dimensional shoulder motion

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ABSTRACT

Background: Rotator cuff disease is associated with changes in kinematics, but the effect of a rotator cuff tear and its size on shoulder kinematics is still unknown in-vivo.

Methods: In this cross-sectional study, glenohumeral and scapulothoracic kinematics of the affected shoulder were evaluated using electromagnetic motion analysis in 109 patients with 1) subacromial pain syndrome (n=34), 2) an isolated supraspinatus tear (n=21), and 3) a massive rotator cuff tear involving the supraspinatus and infraspinatus (n=54). Mixed models were applied for the comparisons of shoulder kinematics between the three groups during abduction and forward flexion.

Results: In the massive rotator cuff tear group, we found reduced glenohumeral elevation compared to the subacromial pain syndrome (16°; 95% confidence interval 10.5 – 21.2, $P < 0.001$) and the isolated supraspinatus tear group (10°; 95% confidence interval 4.0 – 16.7, $P = 0.002$) at 110° abduction. Reduced glenohumeral elevation in massive rotator cuff tears coincides with an increase in scapulothoracic lateral rotation compared to subacromial pain syndrome (11°; 95% confidence interval 6.5 – 15.2, $P < 0.001$) and supraspinatus tears (7°; 95% confidence interval 1.8 – 12.1, $P = 0.012$). Comparable differences were observed for forward flexion. No differences in glenohumeral elevation were found between the subacromial pain syndrome and isolated supraspinatus tear group during arm elevation.

Conclusion: The massive posterosuperior rotator cuff tear group had substantially less glenohumeral elevation and more scapulothoracic lateral rotation compared to the other groups. These observations suggest that the infraspinatus is essential to preserve glenohumeral elevation in the presence of a supraspinatus tear. Shoulder kinematics are associated with rotator cuff tear size and may have diagnostic value.

INTRODUCTION

Shoulder pain is the most prevalent cause for musculoskeletal upper extremity complaints within our society, and coincides with reduced arm function during activities of daily living and work.[22, 40] Most shoulder complaints are attributed to pathologic changes in the rotator cuff (RC).[47] Main clinical entities of RC disease comprise subacromial pain syndrome (SAPS) and RC tears.[7, 47] The latter is clinically divided for prognostic and therapeutic purposes in isolated supraspinatus tears and massive RC tears, in which the supraspinatus tear usually extends towards the infraspinatus tendon (i.e. massive posterosuperior RC tear).[1]

The RC provides essential forces to minimize glenohumeral (GH) translations (i.e. stability) and torques for shoulder motion.[43, 48] A disturbed equilibrium of RC forces in RC tears may endanger shoulder stability. Computer and cadaver simulations have shown the negative impact of RC tears involving the supraspinatus and infraspinatus muscle (i.e. massive posterosuperior RC tears) on joint reaction forces and GH joint stability.[2, 12, 27, 39, 43, 46] Clinically, lost GH stability is marked by excessive proximal migration of the humeral head.[13] Whereas proximal migration and range of motion are clinically used for diagnostic purposes to diagnose a patient with an RC tear, the coordination of shoulder motion is generally not assessed. Knowledge on how the extent of an RC tear affect the coordination of shoulder motion may provide additional diagnostic information. Some research has been done to study kinematics in RC tears, but those studies do not take into account the effect of tear size when evaluating kinematics.[31, 41] In addition, patients with massive posterosuperior RC tears have been extensively studied in 3D motion analyses.[36] Consequently, the link between increasing RC tear size, with a subsequent reduction of infraspinatus forces, and in-vivo shoulder kinematics has still to be determined in order to support experimental findings in simulated RC tears.[30]

GH stability and mobility in massive RC tears may require different kinematics in contrast to the other two clinical subgroups.[43] GH-joint stability may improve by reduced scapular lateral rotation *(i.e. increased GH elevation)* when the force vector will be directed more towards the centre of the glenoid, whereas mobility may improve by increased scapular lateral rotation *(i.e. reduced GH elevation)* as a result of deltoid lengthening.[19, 42, 43]

The aim of our study was to study the effect of RC tears and its size on shoulder kinematics by comparing three clinically distinct groups with RC related pain: SAPS (i.e. excluding full-thickness RC tears [7]), isolated supraspinatus tears and massive posterosuperior RC tears. We asked: (1) Do patients with massive posterosuperior RC tears exhibit reduced glenohumeral elevation compared to patients with an intact RC (i.e. SAPS) or isolated supraspinatus tear? (2) Is scapulothoracic lateral rotation dissimilar between patients with SAPS (i.e. intact RC), an isolated supraspinatus tear or a massive RC tear? We hypothesised that patients with a massive posterosuperior RC tear would have a reduced contribution of

GH elevation (i.e. increased scapular lateral rotation) to the overall elevation compared to patients with SAPS or an isolated tear of the supraspinatus.

MATERIALS AND METHODS

Participants

In this cross-sectional study, shoulder kinematics were evaluated in 109 consecutive patients with RC pathologies, who visited the Laboratory for Kinematics and Neuromechanics (Leiden University Medical Centre, Leiden, the Netherlands) between April 2003 and October 2012. Patients were recruited according to one out of three protocols. Based on these protocols, three diagnostic subgroups were selected after a thorough physical examination, AP shoulder radiography and magnetic resonance arthrography (MRA). Each subgroup had its specific inclusion and exclusion criteria:

Group I consisted of thirty-four patients with SAPS with an MRA proven intact RC, who were recruited at the outpatient clinic of three regional hospitals (Leiden University Medical Centre, Medical Centre Haaglanden and Alrijne Hospital)[7]. SAPS was clinically defined by a positive Hawkins and Neer impingement test in combination with at least one of the following clinical signs of SAPS: pain during shoulder movements, pain at night or incapable of lying on the shoulder, painful arc, diffuse pain at palpation of the greater tuberosity, scapular dyskinesis, a positive full/empty can test or a positive Yocum test. Only patients aged between 35 and 60 years with unilateral shoulder complaints for at least 3 months were included. Exclusion criteria were insufficient Dutch language skills, prior shoulder surgery, shoulder fracture or dislocation, radiculopathy, frozen shoulder, electronic implants, (inflammatory) GH or symptomatic acromioclavicular osteoarthritis, calcific tendinitis, full-thickness RC tear, PASTA lesion, labrum or ligament pathology, pulley lesion, biceps tendinopathy, os acromiale and tumour.

Group II consisted of twenty-one patients with an isolated full-thickness and degenerative supraspinatus tear who were included at the Medical Centre Haaglanden when suffering from impaired function and pain (i.e. Davidson type I or II).[3] All patients were scheduled for surgical RC repair and the extent of RC tears was intra-operatively confirmed.

Group III consisted of fifty-four patients with a massive posterosuperior RC tear recruited at two hospitals (Leiden University Medical Centre and Medical Centre Haaglanden). A massive posterosuperior RC tear was defined according to the criteria of Davidson et al. as type 3 full-thickness posterosuperior tear, with a tear width of ≥20mm, a length of ≥20mm, and partial or complete detachment of the infraspinatus insertion side.[3] The teres minor muscle was intact in all participants. Patients suffered from either pain or impaired shoulder function during activities of daily living.

Exclusion criteria in group II and III were: insufficient Dutch language skills, a history of shoulder surgery, fracture or dislocation, radiculopathy, subscapularis tear, reduced passive RoM (clinically determined by comparing the affected to unaffected shoulder), muscle dystrophy, (inflammatory) symptomatic GH or acromioclavicular osteoarthritis, tumour and electronic implants.

Baseline characteristics are presented in Table 1. Patients may have participated in earlier studies.[5, 20, 42, 44, 45] The medical ethics committees of Leiden University Medical Centre (P07.123 & P09.227) and Zuidwest Holland (P07.116) approved all examinations. Written informed consent was obtained from all participants.

Table 1. Baseline characteristics

Characteristics	**SAPS** (n=34)		**Supraspinatus tear** (n=21)		**Massive RC tear** (n=54)	
Age, mean ± SD, yrs.	50	(6)	58	(9)	61	(7)
Female, n (%)	19	(56)	12	(57)	20	(37)
Left side affected, n (%)	14	(41)	10	(48)	19	(35)
Dominant side affected, n (%)	21	(62)	11	(52)	35	(65)
VAS for pain during movement mean ± SD, mm.	39	(24)	59	(31)	47	(27)

Measurement set-up

Kinematics in affected shoulders were evaluated in a standardized seated position with the Flock of Birds (FoB) 3D electromagnetic tracking system (Ascension Technology Inc., Milton, Vermont, USA). An extended range transmitter generated an electromagnetic field to record the position and orientation of seven wired sensors at about 30Hz in order to examine bilateral shoulder motion with six degrees of freedom. Motion of the shoulder girdle was recorded with three wired sensors attached to both arms. One sensor was adhered to the flat cranio-lateral surface of the acromion with self-adhesive tape. Other sensors were attached to the flat surface of the distal humerus and the dorsal side of the distal forearm with a strap with hook-and-loop fastener. The seventh sensor was attached to the manubrium sternii with self-adhesive tape. Subsequently, twenty-four bony landmarks were manually palpated and digitized as recommended by the International Society of Biomechanics (ISB).[50] Digitization of bony landmarks is accomplished by calculating the coordinates of bony landmark using position and orientation of a sensor mounted on a stylus.[32] All methodology has been validated earlier.[4, 16, 32-35] We visualized the places of sensors in Supplement 1, landmarks were digitized according to the ISB guidelines.[50]

Measurements

Patients were requested to perform four bilateral unconstraint (i.e. not guided) movements: elevation in the frontal plane (i.e. abduction), forward flexion, backward flexion (i.e. extension) and external rotation of the upper arm with the humerus at least 40^0 elevated and the elbow 90^0 flexed. Each movement was performed twice. Range of motion was assessed for all shoulder movements in the affected shoulder. Shoulder kinematics, including GH and ST motion, were assessed during abduction and forward flexion.

Data processing

Bony landmarks were used to reconstruct a local Cartesian right-handed coordinate system for the thorax, scapula and humerus according to the ISB recommendations.[50] Left segments were mirrored to the right. Local coordinate systems consisted of axis pointing anteriorly (X_t), superiorly (Y_t) and laterally to the right (Z_t). Humerothoracic motion, ST motion and GH motion were calculated according to the appropriate Euler or Cardan sequence.[50]

For humerothoracic and GH motion an Euler sequence (Y-X-Y) was applied in a moving system. Humerothoracic motion was described as follows: 1) plane of elevation is rotation around the thoracic Y-axis, 0° represents elevation in the frontal plane and 90° elevation in the parasagittal plane; 2) elevation is negative rotation around the rotated humeral X'-axis; 3) internal rotation is positive rotation around the rotated humeral Y"-axis. GH motion was described as follows: 1) GH plane of elevation is rotation around the scapular Y-axis; 2) GH elevation is negative rotation around the humeral X'-axis; 3) internal GH rotation is positive rotation around the longitudinal humeral Y"-axis. For ST motion a fixed Cardan sequence (Y-X-Z) was applied: 1) internal rotation (i.e. protraction) is positive rotation around the thoracic Y-axis; 2) lateral rotation (i.e. upward rotation) is negative rotation around the scapular X'-axis; 3) posterior tilt is positive rotation around the scapular Z"-axis. In contrast to Wu et al., we expressed humerothoracic elevation, ST lateral rotation and GH elevation as positive motion.[50] Custom-made MATLAB software (2013b release, The MathWorks Inc., Natick, Massachusetts, USA) was used for data processing.

3D shoulder kinematics were calculated during arm abduction and forward flexion and an average of repeated movements was used. ST and GH motion were recorded up to 110° of humerothoracic elevation since accuracy of the acromion sensor decreases at higher elevation as a consequence of skin movement artifacts.[17] Data obtained during abduction (i.e. plane of elevation $< 30°$) and forward flexion (i.e. plane of elevation $> 45°$) were assessed for out of plane movements, data within the plane of interest qualified for our analysis. A mean position for ST and GH motion was interpolated for nine intervals of 10° humerothoracic elevation within the range of 20° – 110°. Since we report on the motion starting from the initial position at 20° – 30°, we subtracted the initial mean GH or ST angle at 20-30° (i.e. offset) from successive angles and evaluated shoulder kinematics within the range of 30° – 110° of humerothoracic elevation. Missing data, due to an inability to raise the arm up to

110°, related to our dependent variable (Supplement 2). Hence, we conducted a stratified analysis using data of all patients and an analysis using data from a subgroup of patients who was able to fully raise their arm up to 110°. Since conclusions based on both analyses with respect to GH (Supplement 3) and ST (Supplement 4) kinematics were comparable, we present our analysis using all patients. From the 109 patients, abduction and forward flexion were <30° in 6 and 8 patients, respectively. The numbers of patients with missing data are described within the supplements.

Statistical analysis

We conducted one-way ANOVAs to compare maximal humerothoracic RoM between three RC pathologies. To account for unequal variance between the groups, we used Welch F tests. In case of significance, we used Games-Howell post-hoc tests to assess the differences. ST and GH rotations were compared between the three RC pathologies with a linear mixed model. Mixed model analysis is a regression model that deals with correlated errors between various intervals while moving the arm (i.e. repeated measures) using a correlation matrix.[49] An autoregressive covariance structure of order one with heterogeneous variances was used.[49] The dependent variable was a single ST or GH rotation. In our primary analysis, we investigated humerothoracic elevation interval and the interaction between RC pathology and humerothoracic elevation interval as fixed effects. The repeated factor was the humerothoracic elevation interval. Shoulder movements were unconstrained because guided movements do not represent daily life motion. Consequently, slight differences in plane of elevation and axial humeral rotation between subjects occurred. Since out of plane elevation and axial humeral rotation may affect shoulder kinematics, we adjusted for humerothoracic rotations by including these rotations as a covariate.[9, 24] In our secondary analysis, we also adjusted for age, sex and whether the dominant shoulder was involved. Mean difference between the RC pathologies in GH and ST orientation were calculated at each humerothoracic elevation angle. IBM SPSS statistics for Windows (version 20.0, IBM Corp, 2011, Armonk, New York, USA) was used. A two-sided P value of < 0.05 was considered statistically significant.

RESULTS

Humerus range of motion (RoM)

Humerothoraric abduction and forward flexion were lower in the massive posterosuperior RC tear group compared to SAPS (Figure 1). External rotation was significantly reduced in patients with a massive posterosuperior RC tear compared to patients with SAPS and an isolated supraspinatus tear. Backward flexion did not differ between the conditions.

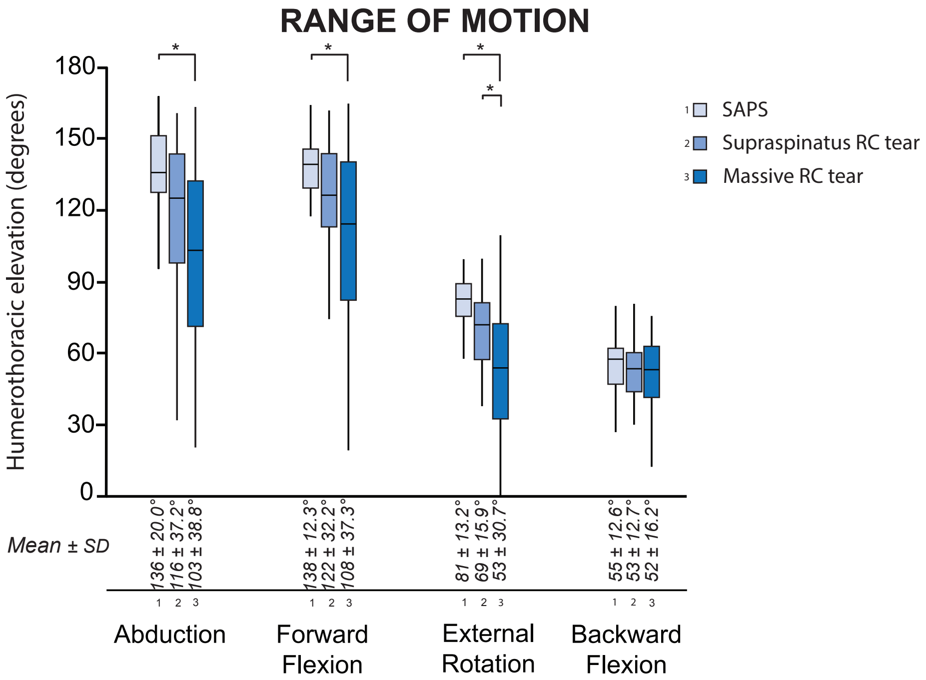

Figure 1. Boxplots show the maximal humerothoracic ROM with the median, interquartile range and range in patients with SAPS (N=34), a supraspinatus RC tear (N=21) and a massive posterosuperior RC tear (N=54).
* Statistically significant.

Do patients with a massive tear exhibit reduced glenohumeral elevation compared to patients with an intact RC or isolated supraspinatus tear?

GH elevation was significantly reduced in patients with a massive posterosuperior RC tear compared to SAPS and an isolated supraspinatus tear during abduction as well as during forward flexion (Figure 2A and Figure 2B). From 30° to 110° of abduction, there was 3° to 16° more GH elevation in the SAPS group and 3° to 10° more GH elevation in the supraspinatus tear group (Table 2). During forward flexion, GH elevation was also significantly reduced in patients with a massive posterosuperior RC tear compared to patients with SAPS (i.e. 2° to 12°) and supraspinatus tears (i.e. 4° to 10°) compared to massive RC tears (Table 2). No differences in GH elevation were found between SAPS and supraspinatus RC tear patients (Table 2). GH plane of elevation and GH internal rotation were not different between SAPS, supraspinatus tears and massive posterosuperior RC tears (Figure 2).

Is scapulothoracic lateral rotation different between patients with SAPS, an isolated supraspinatus tear or a massive RC tear?

Patients with a massive posterosuperior RC tear revealed significantly more ST lateral rotation (i.e. upward rotation) compared to the other shoulder conditions for both abduction

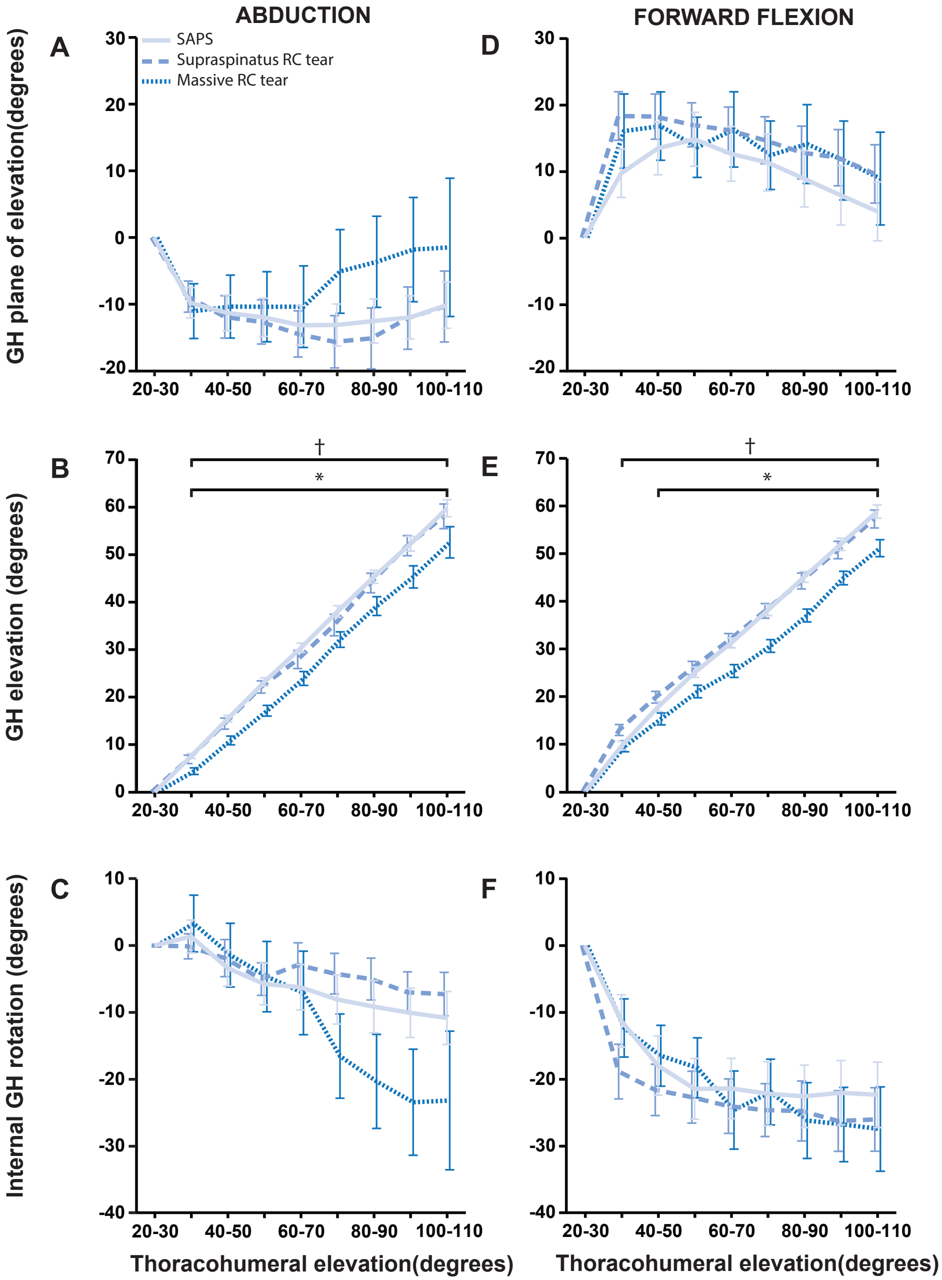

Figure 2. Glenohumeral motion (± standard error) from the initial position at 20-30°of humerothoracic elevation in patients with SAPS (straight line), an isolated supraspinatus RC tear (dashed line) and a massive posterosuperior RC tear (small-dashed line) during abduction (panel A) and forward flexion (panel B). Mean initial positions are described for SAPS (▲), isolated supraspinatus tears (■) and massive RC tears (▼) at the left. Patients with a massive posterosuperior RC tear demonstrated significantly less glenohumeral elevation compared to SAPS (*) and isolated supraspinatus tears (†).

Table 2. Difference in glenohumeral elevation

Abduction							
		Massive RC tear (n=48) vs.				SAPS (n=34) vs.	
		SAPS (n = 34)		Supraspinatus tear (n = 21)		Supraspinatus tear (n = 21)	
		Mean difference (°, 95% CI)	P value	Mean difference (°, 95% CI)	P value	Mean difference (°, 95% CI)	P value
30-40°	†	3 (1.5 – 5.4)	0.001*	3 (0.9 – 5.4)	0.008*	-0 (-2.7 – 2.1)	0.806
	‡	3 (1.2 – 5.6)	0.003*	3 (0.6 – 5.4)	0.014*	-0 (-3.0 – 2.2)	0.749
40-50°	†	6 (2.9 – 8.6)	<0.001*	4 (1.1 – 7.7)	0.010*	-1 (-4.9 – 2.1)	0.442
	‡	6 (2.7 – 8.8)	<0.001*	4 (0.8 – 7.7)	0.015*	-1 (-5.1 – 2.2)	0.417
50-60°	†	8 (4.7 – 11.3)	<0.001*	6 (2.1 – 9.8)	0.003*	-2 (-6.1 – 2.0)	0.317
	‡	8 (4.5 – 11.4)	<0.001*	6 (1.8 – 9.8)	0.004*	-2 (-6.4 – 2.0)	0.303
60-70°	†	10 (5.7 – 13.3)	<0.001*	6 (1.4 – 10.4)	0.010*	-4 (-8.3 – 1.1)	0.130
	‡	10 (5.5 – 13.5)	<0.001*	6 (1.1 – 10.4)	0.015*	-4 (-8.7 – 1.1)	0.129
70-80°	†	11 (7.3 – 15.4)	<0.001*	7 (2.2 – 11.8)	0.005*	-4 (-9.4 – 0.7)	0.092
	‡	11 (7.1 – 15.6)	<0.001*	7 (2.0 – 11.8)	0.007*	-4 (-9.7 – 0.7)	0.091
80-90°	†	13 (8.3 – 17.1)	<0.001*	8 (3.1 – 13.4)	0.002*	-4 (-9.8 – 1.0)	0.109
	‡	13 (8.1 – 17.3)	<0.001*	8 (2.8 – 13.5)	0.003*	-4 (-10.2 – 1.0)	0.108
90-100°	†	14 (9.5 – 19.1)	<0.001*	10 (3.9 – 15.3)	0.001*	-5 (-10.6 – 1.2)	0.114
	‡	14 (9.4 –19.4)	<0.001*	9 (3.6 – 15.3)	0.002*	-5 (-10.9– 1.2)	0.112
100-110°	†	16 (9.5 – 19.1)	<0.001*	10 (4.0 – 16.7)	0.002*	-6 (-12.1 – 0.9)	0.092
	‡	16 (10.4 – 21.5)	<0.001*	10 (3.7 – 16.7)	0.002*	-6 (-12.5 – 0.9)	0.090
Forward Flexion							
		Massive RC tear (n=48) vs.				SAPS (n=33) vs.	
		SAPS (n = 33)		Supraspinatus tear (n = 20)		Supraspinatus tear (n = 20)	
		Mean difference (°, 95% CI)	P value	Mean difference (°, 95% CI)	P value	Mean difference (°, 95% CI)	P value
30-40°	†	2 (-1.3 – 4.9)	0.247	4 (0.7 – 7.9)	0.021*	2 (-1.4 – 6.3)	0.205
	‡	3 (-0.4 – 7.0)	0.084	4 (0.7 – 8.2)	0.021*	1 (-3.1 – 5.3)	0.591
40-50°	†	4 (0.2 – 7.0)	0.036*	5 (1.5 – 9.5)	0.007*	2 (-2.4 – 6.1)	0.385
	‡	5 (1.1 – 9.0)	0.012*	6 (1.5 – 9.6)	0.007*	1 (-4.0 – 5.1)	0.825
50-60°	†	5 (1.5 – 8.7)	0.005*	6 (2.1 – 10.5)	0.004*	1 (-3.3 – 5.6)	0.605
	‡	7 (2.5 – 10.7)	0.002*	6 (2.1 – 10.7)	0.004*	-0 (-5.0 – 4.6)	0.938
60-70°	†	6 (2.2 – 9.3)	0.002*	6 (2.2 – 10.6)	0.003*	1 (-3.7 – 5.1)	0.754
	‡	7 (3.1 – 11.3)	0.001*	7 (2.3 – 10.8)	0.003*	-1 (-5.4 – 4.1)	0.784
70-80°	†	8 (4.3 – 11.9)	<0.001*	8 (3.8 – 12.7)	<0.001*	0 (-4.6 – 4.8)	0.960
	‡	10 (5.3 – 13.9)	<0.001*	8 (3.8 – 12.9)	<0.001*	-1 (-6.2 – 3.8)	0.624
80-90°	†	9 (5.6 – 13.2)	<0.001*	9 (4.3 – 13.2)	<0.001*	-1 (-5.4 – 4.0)	0.770
	‡	11 (6.5 – 15.1)	<0.001*	9 (4.3 – 13.3)	<0.001*	-2 (-7.0 – 2.9)	0.416
90-100°	†	10 (6.2 – 14.3)	<0.001*	9 (3.8 – 13.4)	0.001*	-2 (-6.7 – 3.4)	0.523
	‡	12 (7.2 – 16.3)	<0.001*	9 (3.9 – 13.6)	0.001*	-3 (-8.3 – 2.3)	0.267
100-110°	†	12 (7.1 – 16.1)	<0.001*	10 (4.3 – 14.9)	0.001*	-2 (-7.6 – 3.6)	0.475
	‡	13 (8.1 – 18.0)	<0.001*	10 (4.4 – 15.1)	0.001*	-3 (-9.2 – 2.4)	0.252

Abbreviations: RC, rotator cuff; vs. versus; CI, confidence interval.

* Statistically significant

† Mixed model analysis: Humerothoracic elevation angle, RC pathology (i.e. SAPS, supraspinatus tear or massive RC tear) × humerothoracic elevation angle, plane of elevation and humeral axial rotation were investigated as fixed effects.

‡ Mixed model analysis (adjusted for age, sex and hand dominancy): Humerothoracic elevation angle, RC pathology (i.e. SAPS, supraspinatus tear or massive RC tear) × humerothoracic elevation angle, plane of elevation, humeral axial rotation, age, sex (male or female) and dominant shoulder affected (yes or no) were investigated as fixed effects.

Table 3. Difference in scapulothoracic lateral rotation

Abduction

		Massive RC tear (n=48) vs.				SAPS (n=34) vs.	
		SAPS (n = 34)		Supraspinatus tear (n = 21)		Supraspinatus tear (n = 21)	
		Mean difference (°, 95% CI)	P value	Mean difference (°, 95% CI)	P value	Mean difference (°, 95% CI)	P value
30-40°	†	-2 (-3.4 – -0.5)	0.010*	-2 (-3.3 – 0.1)	0.066	0 (-1.5 – 2.1)	0.703
	‡	-2 (-3.2 – 0.4)	0.058	-1 (-3.1 – 0.4)	0.123	0 (-1.7 – 2.1)	0.851
40-50°	†	-4 (-6.2 – -1.7)	0.001*	-3 (-5.3 – -0.1)	0.040*	0 (-1.5 – 4.0)	0.384
	‡	-4 (-5.9 – 0.2)	0.003*	-2 (-5.1 – 0.2)	0.065	1 (-1.8 – 3.9)	0.452
50-60°	†	-6 (-8.5 – -3.0)	<0.001*	-4 (-7.2 – -0.7)	0.017*	2 (-1.6 – 5.2)	0.303
	‡	-5 (-8.2 – -2.5)	<0.001*	-4 (-7.0 – -0.4)	0.027*	2 (-1.8 – 5.1)	0.351
60-70°	†	-8 (-10.7 – -4.3)	<0.001*	-4 (-7.9 – -0.4)	0.030*	3 (-0.6 – 7.3)	0.094
	‡	-7 (-10.5 – -3.9)	<0.001*	-4 (-7.8 – -0.1)	0.045*	3 (-0.8 – 7.3)	0.115
70-80°	†	-9 (-12.0 – -5.4)	<0.001*	-5 (-8.6 – -0.8)	0.018*	4 (-0.1 –8.0)	0.058
	‡	-8 (-11.8 – -4.9)	<0.001*	-5 (-8.5 – -0.5)	0.027*	4 (-0.4 –8.1)	0.073
80-90°	†	-10 (-14.0 – -6.8)	<0.001*	-6 (-10.4 – -2.0)	0.004*	4 (-0.2 – 8.5)	0.063
	‡	-10 (-13.7 – -6.4)	<0.001*	-6 (-10.3 – -1.7)	0.007*	4 (-0.5 – 8.6)	0.078
90-100°	†	-11 (-14.8 – -7.0)	<0.001*	-7 (-11.5 – -2.1)	0.004*	4 (-0.8 – 8.9)	0.101
	‡	-11 (-14.7 – -6.5)	<0.001*	-7 (-11.4 – -1.9)	0.007*	4 (-1.0 – 8.9)	0.118
100-110°	†	-11 (-15.2 – -6.5)	<0.001*	-7 (-12.1 – -1.9)	0.009*	4 (-1.4 – 9.1)	0.152
	‡	-11 (-15.0 – -6.0)	<0.001*	-7 (-12.0 – -1.5)	0.012*	4 (-1.6 – 9.2)	0.170

Forward Flexion

		Massive RC tear (n=48) vs.				SAPS (n=33) vs.	
		SAPS (n = 33)		Supraspinatus tear (n = 20)		Supraspinatus tear (n = 20)	
		Mean difference (°, 95% CI)	P value	Mean difference (°, 95% CI)	P value	Mean difference (°, 95% CI)	P value
30-40°	†	-3 (-5.8 – 0.2)	0.067	-1 (-4.8 – 2.2)	0.461	1 (-2.2 – 5.2)	0.430
	‡	-4 (-7.1 – -0.2)	0.038*	-2 (-5.1 – 2.0)	0.381	2 (-1.8 – 6.1)	0.294
40-50°	†	-4 (-6.6 – -0.7)	0.017*	-2 (-5.4 – 1.6)	0.288	2 (-1.9 – 5.5)	0.346
	‡	-5 (-8.0 – -1.1)	0.011*	-2 (-5.6 – 1.4)	0.236	2 (-1.6 – 6.4)	0.234
50-60°	†	-5 (-7.5 – -1.6)	0.003*	-2 (-5.9 – 1.1)	0.180	2 (-1.5 – 5.9)	0.247
	‡	-5 (-8.9 – -2.0)	0.002*	-3 (-6.1 – 0.9)	0.145	3 (-1.2 – 6.8)	0.163
60-70°	†	-6 (-8.9 – -2.9)	<0.001*	-3 (-6.2 – 0.8)	0.125	3 (-0.5 – 6.9)	0.093
	‡	-7 (-10.2 – -3.3)	<0.001*	-3 (-6.5– 0.6)	0.099	4 (-0.2 – 7.8)	0.060
70-80°	†	-8 (-10.6 – -4.7)	<0.001*	-4 (-7.5 – -0.5)	0.024*	4 (-0.0 – 7.4)	0.052
	‡	-9 (-12.0 – -5.1)	<0.001*	-4 (-7.8 – -0.7)	0.019*	4 (0.3 – 8.3)	0.033*
80-90°	†	-9 (-11.6 – -5.7)	<0.001*	-4 (-7.8 – -0.8)	0.017*	4 (0.6 – 8.1)	0.022*
	‡	-9 (-13.0 – -6.0)	<0.001*	-5 (-8.1 – -1.0)	0.013*	5 (1.0 – 8.9)	0.014*
90-100°	†	-9 (-12.5 – -6.5)	<0.001*	-3 (-6.8 – 0.3)	0.071	6 (2.5 – 9.9)	0.001*
	‡	-10 (-13.8 – -6.8)	<0.001*	-3 (-7.0 – 0.1)	0.059	7 (2.9 – 10.8)	0.001*
100-110°	†	-9 (-11.9 – -5.8)	<0.001*	-3 (-6.7 – 0.4)	0.086	6 (2.0 – 9.5)	0.003*
	‡	-10 (-13.2 – -6.1)	<0.001*	-3 (-6.9 – 0.3)	0.074	6 (2.4 – 10.4)	0.002*

Abbreviations: RC, rotator cuff; vs. versus; CI, confidence interval.

* Statistically significant.

† Mixed model analysis: Humerothoracic elevation angle, RC pathology (i.e. SAPS, supraspinatus tear or massive RC tear) × humerothoracic elevation angle, plane of elevation and humeral axial rotation were investigated as fixed effects.

‡ Mixed model analysis (adjusted for age, sex and hand dominancy): Humerothoracic elevation angle, RC pathology (i.e. SAPS, supraspinatus tear or massive RC tear) × humerothoracic elevation angle, plane of elevation, humeral axial rotation, age, sex (male or female) and dominant shoulder affected (yes or no) were investigated as fixed effects.

and forward flexion (Figure 3A and Figure 3B). From 30° to 110° of abduction, there was 2° to 11° and 2° to 7° more lateral rotation in the massive posterosuperior RC tear group compared to the SAPS group and isolated supraspinatus tear group, respectively (Table 3). More lateral rotation was found during forward flexion compared to the SAPS group (i.e.

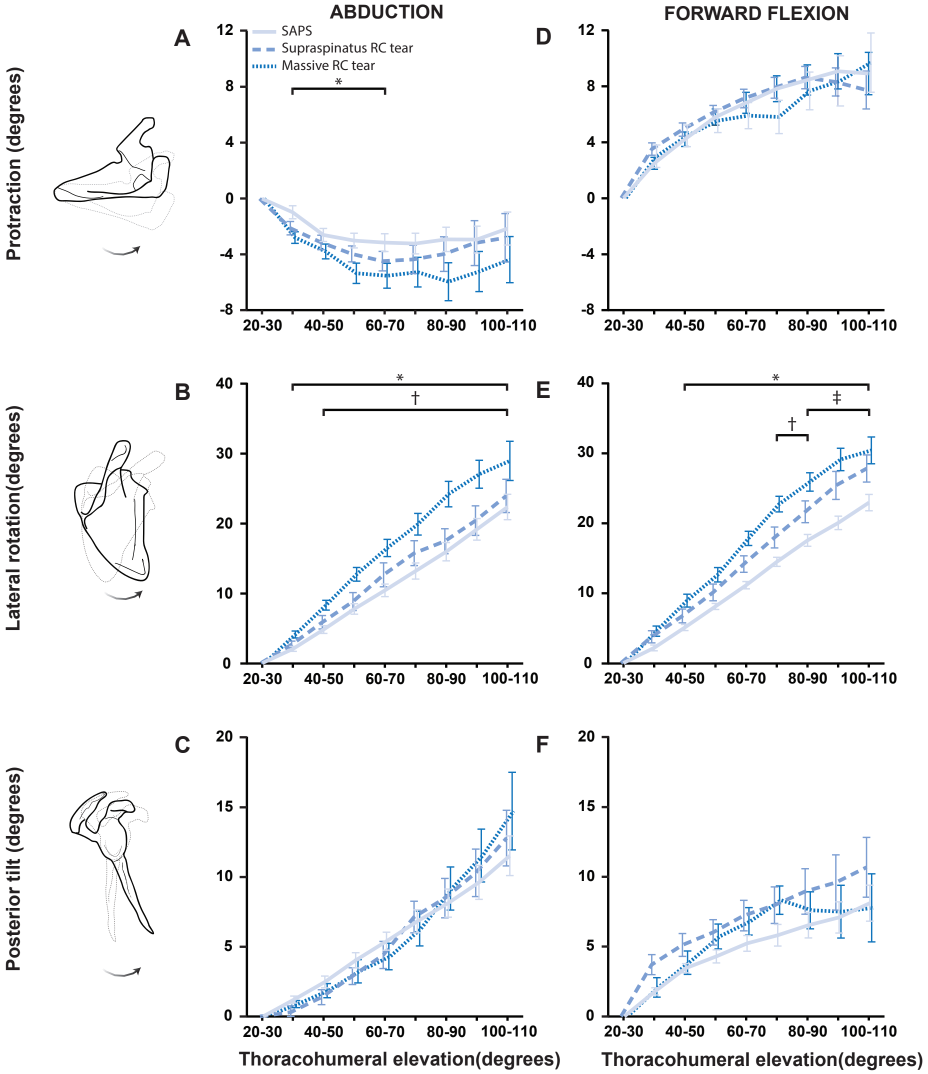

Figure 3. Scapulothoracic motion (± standard error) from the initial position at 20-30°of humerothoracic elevation in patients with SAPS (straight line), a supraspinatus RC tear (dashed line) and a massive posterosuperior RC tear (small-dashed line) during abduction (panel A) and forward flexion (panel B). Statistically significant difference between patients with a massive RC tear and SAPS (*) or supraspinatus RC tears (†). Statistically significant difference between patients with a supraspinatus RC tear and SAPS (‡).

3° to 9°) and supraspinatus tear group (e.g. 4° at 70-80°) (Table 3). Patients with an isolated supraspinatus tear had more lateral rotation during forward flexion from 80° to 110° elevation (i.e. 4° to 6°) compared to patients with SAPS (Table 3).

Less ST internal rotation was demonstrated from 30° to 70° abduction (i.e. 1° to 2°) in patients with massive posterosuperior RC tears compared to patients with SAPS during abduction. Posterior tilt did not significantly differ between the three RC diseases (Figure 3).

DISCUSSION

In the present study we aimed to differentiate kinematics between three distinct RC diseases in order to improve the understanding of shoulder kinematics in patients with symptomatic RC disease. Patients with a massive posterosuperior RC tear showed less GH elevation during arm elevation compared to patients with SAPS or isolated supraspinatus tears. The SAPS and isolated supraspinatus tear groups did not differ with respect to GH elevation. Reduced GH elevation in massive posterosuperior RC tears is accompanied by a marked increase in ST lateral rotation.

Kinematics in patients

Our study supports the findings in simulated massive posterosuperior RC tears created after a suprascapular nerve block in healthy volunteers.[30] McCully et al. showed a decline in GH elevation and increase in ST lateral rotation in simulated massive posterosuperior RC tears.[30] Since the infraspinatus muscle has a direct impact on the GH joint and does not directly control ST motion, McCully et al. concluded that an increase in ST lateral rotation should be compensatory in nature.[30] In line with most kinematic evaluations we observed small differences in GH and ST motion between isolated supraspinatus tears and patients with SAPS.[6, 11, 31, 37, 51] In the literature, no differences in shoulder kinematics were previously found in patients with a massive RC tear compared to healthy volunteers.[36] Most studies investigated kinematics in groups without categorising the type of RC tear, causing heterogeneity.[6, 31, 36, 37] Heterogeneity might result in additional variance, a lower statistical power, and consequently might lead to other conclusions.[6, 31, 36, 37] As an alternative, we proposed to stratify patients according to diagnostic subgroups based on our biomechanical rationale.[43] Importantly, findings suggest that physicians may discriminate massive RC tears from less extensive RC tears by observing coordination of shoulder motion, making kinematic analysis a possible future diagnostic tool.

We observed the least amount of ST lateral rotation and greater GH elevation in patients with SAPS, which was also expected based on our biomechanical hypothesis. Conflicting results have been reported for ST kinematics in patients with SAPS and in subjects without shoulder pain has been shown to be dissimilar.[8, 10, 21, 23, 25, 26, 29] A major strength of our study was that we evaluated the condition of the RC using MR imaging, and confirmed that the RC was intact in all SAPS patients. Because physical examination alone lacks accuracy for a correct identification of an RC tear, and an RC tear may adversely affect shoulder kinematics, we consider imaging of the RC crucial to reveal the presence of RC tears in this kinematic study[38]. Though, subjects with SAPS might exhibit pathologic kinematics as well, even with the RC being intact. Those differences in kinematics between SAPS patients and asymptomatic individuals are still unclear and need further research.[8, 11, 21, 23, 25, 26, 29]

A biomechanical perspective

Earlier in silico and cadaver studies have shown a substantial increase in forces generated by the posterior RC (i.e. residual infraspinatus or teres minor) to maintain a congruent articulation of the GH joint in RC tears.[12, 14, 28, 39, 43, 46] The infraspinatus, teres minor and subscapularis muscles prevent excessive proximal migration of the humeral head in isolated supraspinatus tears.[2, 12, 15, 28, 39, 43, 46] If an RC tear extends beyond the supraspinatus into the infraspinatus muscle, the teres minor is suggested to become hypertrophic to compensate for the loss of stabilizing infraspinatus forces.[18] Loss of glenohumeral elevation in massive RC tears at equal arm position reflects a redistribution of muscle torques and thus altered coordination, since net arm torque remains similar. In massive RC tears, the deltoid muscle compensates for lost RC torques during elevation of the arm.[43, 44] As a compensation strategy, lengthening of the deltoid seems favourable to generate sufficient torques for arm elevation.[19] When increasing relative scapular lateral rotation at equal total arm abduction (i.e. adduction movement of the scapula relative to the humerus), the length of the deltoid muscle may increase towards its optimal length, optimizing abduction moment capacity.[19] The latter might be an explanation for our findings. Also, co-activation of the latissimus dorsi or teres major might compromise GH elevation in massive posterosuperior RC tears. Co-activation of shoulder adductors was postulated to prevent proximal migration of the humerus.[42, 44, 45] Nevertheless, the exact biomechanics that contribute to our in-vivo observations are not yet fully understood.

Limitations and future work

This study has some limitations. Shoulder kinematics were not investigated in subjects without RC disease. Missing data, caused by incomplete elevation, related to the investigated pathology and this affected the estimations of the effect. However, our stratified analysis yields similar conclusions. Furthermore, we subtracted the initial position from successive positions to describe shoulder motion and to correct for differences between groups in initial positions. As a result, we do not report the differences in absolute orientations between pathologies. Alternatively, a non-linear transformation, by using 3D rotation matrices, could be applied to adjust for the two other rotations. Both methods resulted in comparable conclusions based on found differences between groups. Finally, pain and unmeasured factors (i.e. passive soft tissue restriction of GH motion) may be related to the extent of the RC tear and shoulder kinematics. It is unlikely that differences are solely attributed to pain, because patients with a massive posterosuperior RC tear did not report significantly more pain. Although our observations suggest that the infraspinatus is essential to preserve GH elevation in the presence of a supraspinatus tear, this study is unable to prove that lost infraspinatus forces have caused the observed reduction in GH elevation.

Due to our cross-sectional study design, future studies should investigate whether kinematic analyses of shoulder motion are useful for diagnostic purposes. A next step in our research would be to investigate the kinematics in subjects without RC disease and to investigate how kinematics change during life. Muscles around the shoulder joint undergo age-related changes, but it is currently unknown whether those changes have implications for shoulder biomechanics and kinematics.

CONCLUSION

Patients with a massive posterosuperior RC tear had substantially less GH elevation and more ST lateral rotation compared to patients with SAPS as well as those with an isolated supraspinatus tear. No differences were found with respect to GH elevation between patients with isolated supraspinatus tears and SAPS. These observations support the assumed important role of infraspinatus forces in the balance of forces within the GH joint, clinically known as the “transverse force couple”, to preserve GH elevation in the presence of an isolated supraspinatus tear. Since shoulder kinematics are associated with RC tear size, this implies an opportunity to test whether 3D-motion analysis is suitable for diagnostic purposes.

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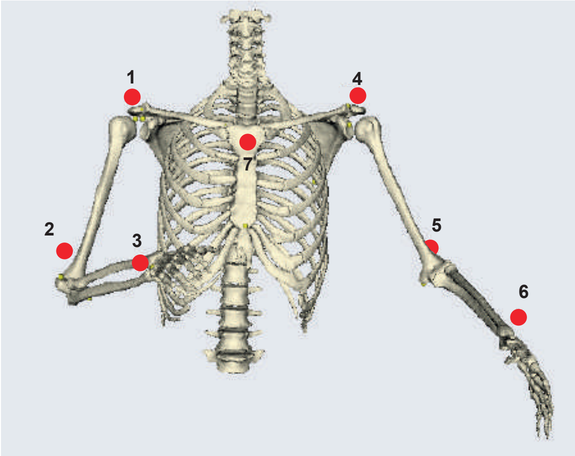
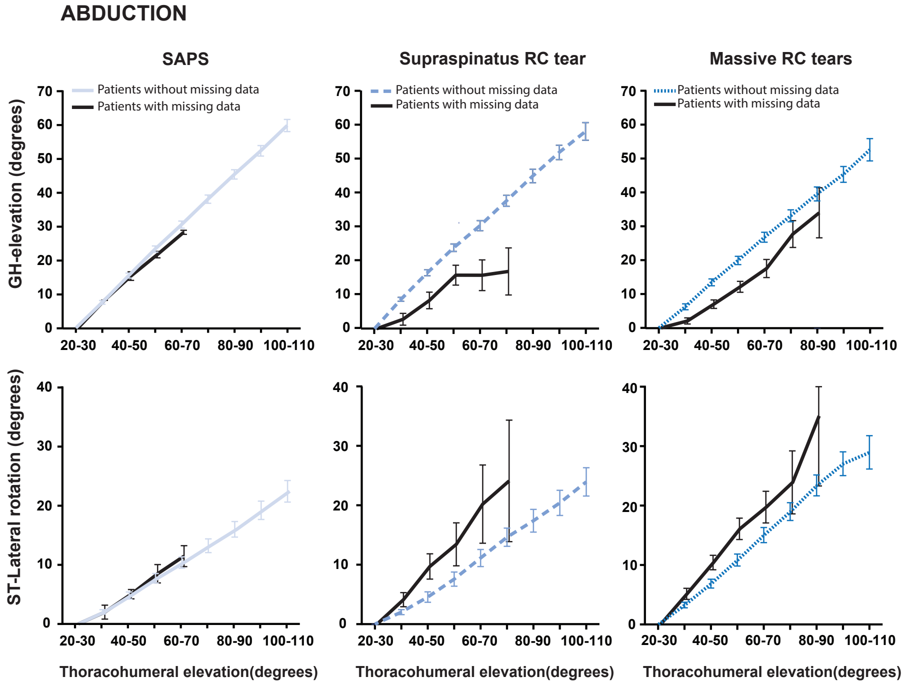
Supplement 1. Schematic drawing of the sensor positions.



Sensors (red dots) were attached to the flat cranio-lateral surface of the acromion (numbers 1 & 4), flat surface of the distal humerus (numbers 2 & 5), the dorsal side of the distal forearm (numbers 3 & 6) and manubrium sternii (number 7).

Supplement 2. Plot of glenohumeral elevation and scapulothoracic lateral rotation in patients with and without missing data.



Mean glenohumeral elevation and scapulothoracic lateral rotation (± standard error) from the initial position at 20-30°of humerothoracic elevation in three RC conditions for included and excluded subjects (black line). Glenohumeral and scapulothoracic motion relate to the ability to elevate up to 110°.

Supplement 3. Differences in glenohumeral elevation in patients without missing data

Abduction

		Massive RC tear (n=48) vs.				SAPS (n=34) vs.	
		SAPS (n = 34)		Supraspinatus tear (n = 21)		Supraspinatus tear (n = 21)	
		Mean difference (°, 95% CI)	P value	Mean difference (°, 95% CI)	P value	Mean difference (°, 95% CI)	P value
30-40°	†	1 (-0.6 – 3.5)	0.171	3 (-0.2 – 5.3)	0.065	1 (-1.2 – 3.8)	0.310
40-50°	†	2 (-0.3 – 4.9)	0.087	3 (-0.1 – 6.4)	0.055	1 (-2.3 – 4.0)	0.582
50-60°	†	4 (0.7 – 6.7)	0.016*	4 (0.5 – 7.8)	0.025*	0 (-3.1 – 4.0)	0.791
60-70°	†	4 (0.8 – 7.4)	0.015*	4 (-0.2 – 7.8)	0.065	-0 (-4.2 – 3.6)	0.885
70-80°	†	5 (1.8 – 9.1)	0.004*	5 (0.5 – 9.5)	0.030*	-0 (-4.8 – 3.9)	0.833
80-90°	†	5 (2.4 – 10.5)	0.002*	6 (1.0 – 11.0)	0.019*	-0 (-5.3 – 4.4)	0.860
90-100°	†	8 (3.3 –12.3)	0.001*	7 (1.6 – 12.8)	0.012*	-1 (-6.0 – 4.8)	0.827
100-110°	†	9 (4.0 – 14.1)	0.001*	8 (1.6 – 14.1)	0.014*	-1 (-7.2 – 4.8)	0.691

Forward Flexion

		Massive RC tear (n=48) vs.				SAPS (n=33) vs.	
		SAPS (n = 33)		Supraspinatus tear (n = 20)		Supraspinatus tear (n = 20)	
		Mean difference (°, 95% CI)	P value	Mean difference (°, 95% CI)	P value	Mean difference (°, 95% CI)	P value
30-40°	†	1 (-2.1 – 4.1)	0.513	4 (-0.1 – 7.2)	0.057	3 (-1.1 – 6.1)	0.167
40-50°	†	2 (-0.8 – 5.3)	0.145	4 (0.8 – 7.9)	0.018*	2 (-1.4 – 5.6)	0.244
50-60°	†	3 (-0.2 – 6.3)	0.064	5 (0.9 – 8.6)	0.016*	2 (-2.1 – 5.5)	0.381
60-70°	†	3 (0.3 – 6.6)	0.032*	5 (1.1 – 8.5)	0.012*	1 (-2.3 – 5.0)	0.464
70-80°	†	5 (1.8 – 8.5)	0.003*	6 (2.0 – 9.9)	0.004*	1 (-3.2 – 4.7)	0.695
80-90°	†	6 (3.1 – 9.7)	<0.001*	6 (2.5 – 10.4)	0.002*	0 (-3.8 – 4.0)	0.966
90-100°	†	7 (3.4 – 10.8)	<0.001*	6 (1.9 – 10.6)	0.006*	-1 (-5.2 – 3.5)	0.707
100-110°	†	8 (4.0 – 12.3)	<0.001*	7 (2.1 – 11.9)	0.005*	-1 (-6.0 – 3.7)	0.640

Abbreviations: RC, rotator cuff; vs. versus; CI, confidence interval.

* Statistically significant difference at $P < 0.05$. † Mixed model analysis: Humerothoracic elevation angle, RC pathology (i.e. SAPS, supraspinatus tear or massive RC tear) × humerothoracic elevation angle, plane of elevation and humeral axial rotation were investigated as fixed effects.

Supplement 4. Differences in scapulothoracic lateral rotation in patients without missing data

Abduction

		Massive RC tear (n=48) vs.				SAPS (n=34) vs.	
		SAPS (n = 34)		Supraspinatus tear (n = 21)		Supraspinatus tear (n = 21)	
		Mean difference (°, 95% CI)	P value	Mean difference (°, 95% CI)	P value	Mean difference (°, 95% CI)	P value
30-40°	†	-1 (-2.6 – 0.4)	0.134	-2 (-3.5 – 0.1)	0.071	-1 (-2.3 – 1.2)	0.537
40-50°	†	-2 (-4.2 – 0.2)	0.077	-2 (-4.9 – 0.5)	0.105	-0 (-2.9 – 2.4)	0.851
50-60°	†	-3 (-5.7 – -0.3)	0.029*	-3 (-6.4 – 0.2)	0.068	-0 (-3.3 – 3.1)	0.961
60-70°	†	-4 (-7.5 – -1.3)	0.006*	-4 (-7.5 – 0.1)	0.057	1 (-2.9 – 4.4)	0.691
70-80°	†	-5 (-8.7 – -2.1)	0.002*	-4 (-8.0 – 0.2)	0.059	1 (-2.5 – 5.4)	0.473
80-90°	†	-7 (-10.4 – -3.2)	<0.001*	-5 (-10.0 – -0.9)	0.019*	1 (-2.9 – 5.9)	0.510
90-100°	†	-7 (-11.4 – -3.2)	0.001*	-6 (-11.1 – -0.9)	0.020*	1 (-3.7 – 6.1)	0.617
100-110°	†	-7 (-11.6 – -2.6)	0.002*	-6 (-11.7 – -0.6)	0.030*	1 (-4.4 – 6.3)	0.732

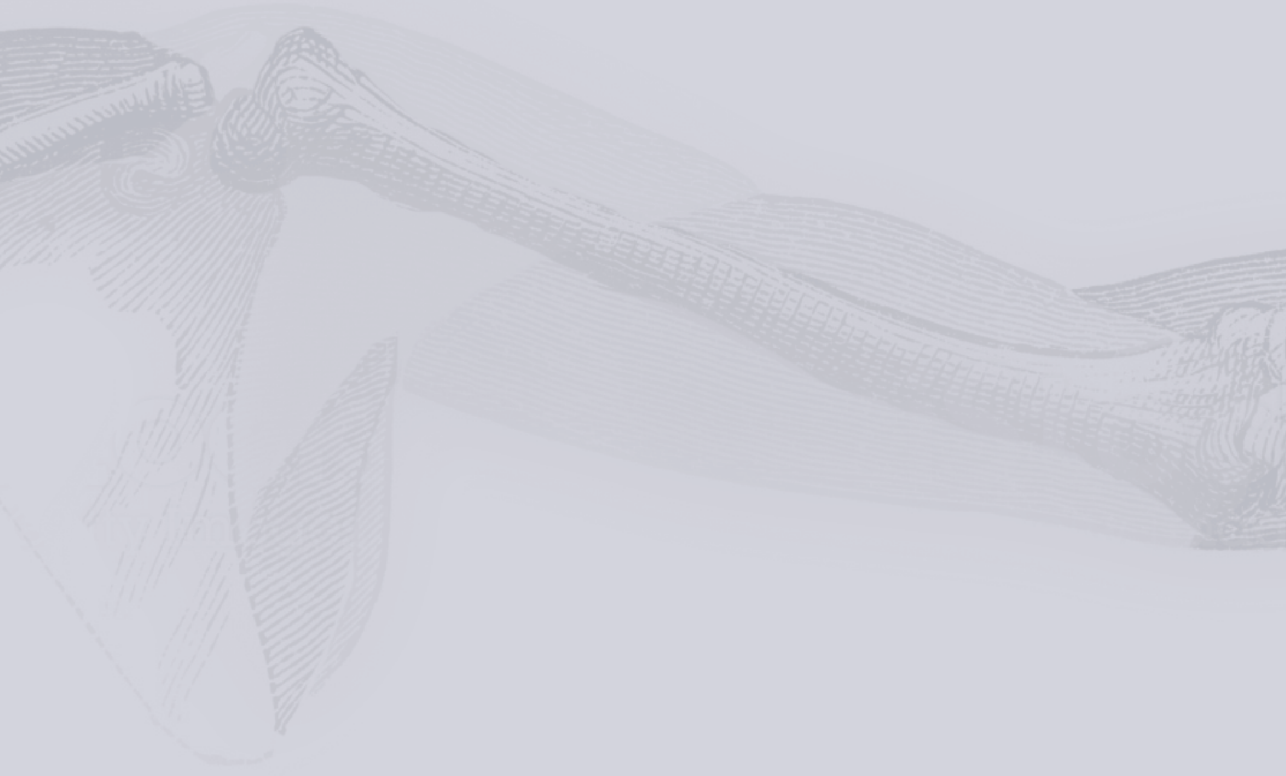
Forward Flexion

		Massive RC tear (n=48) vs.				SAPS (n=33) vs.	
		SAPS (n = 33)		Supraspinatus tear (n = 20)		Supraspinatus tear (n = 20)	
		Mean difference (°, 95% CI)	P value	Mean difference (°, 95% CI)	P value	Mean difference (°, 95% CI)	P value
30-40°	†	-3 (-5.0 – -0.9)	0.005*	-1 (-3.8 – 1.0)	0.240	2 (-0.8 – 3.9)	0.199
40-50°	†	-4 (-6.8 – -1.6)	0.002*	-3 (5.8 – 0.3)	0.075	1 (-1.6 – 4.5)	0.352
50-60°	†	-5 (-7.3 – -2.2)	<0.001*	-3 (-6.2 – -0.1)	0.042*	2 (-1.4 – 4.6)	0.289
60-70°	†	-6 (-8.2 – -3.0)	<0.001*	-3 (-6.4 – -0.3)	0.034*	2 (-0.8 – 5.3)	0.146
70-80°	†	-7 (-10.0 – -4.3)	<0.001*	-4 (-7.5 – -0.8)	0.016*	3 (-0.3 – 6.3)	0.073
80-90°	†	-8 (-11.1 – -5.2)	<0.001*	-5 (-8.0 – -1.1)	0.010*	4 (0.2 – 7.0)	0.040*
90-100°	†	-9 (-12.3 – -5.7)	<0.001*	-3 (-7.4 – 0.4)	0.079	6 (1.6 – 9.4)	0.006*
100-110°	†	-8 (-12.1 – -4.8)	<0.001*	-3 (-7.8 – 0.9)	0.121	5 (0.8 – 9.3)	0.022*

Abbreviations: RC, rotator cuff; vs. versus; CI, confidence interval.

* Statistically significant difference at $P < 0.05$.

† Mixed model analysis: Humerothoracic elevation angle, RC pathology (i.e. SAPS, supraspinatus tear or massive RC tear) × humerothoracic elevation angle, plane of elevation and humeral axial rotation were investigated as fixed effects.



6

The presence of a rotator cuff tear interferes with age-dependent muscle atrophy of intact shoulder muscles

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ABSTRACT

Background: Rotator cuff muscle atrophy is frequently studied, but it is unknown whether redistribution of mechanical load in the presence of a rotator cuff tear influence muscle atrophy that is observed in patients. We hypothesised that in the presence of a supraspinatus tear, redistribution of mechanical load towards teres minor and deltoid slows down atrophy of these muscles over time.

Methods: In this retrospective observational study of 129 patients, we measured the cross-sectional surface-areas on MRI of shoulder muscles in an intact rotator cuff (n=92) and in a supraspinatus-tear group (n=37) with a mean follow-up of 3 ± 1.8 years. Mixed models were applied to evaluate changes in surface-area of the rotator cuff and deltoid with adjustments for age, sex and follow-up time.

Results: In patients with an intact rotator cuff, the mean surface-area of the teres minor decreased 6mm^2/year (95% confidence interval 0.7 – 11.1, $P = 0.026$) and the mean deltoid surface-area decreased 75mm^2/year (95% confidence interval 24.5 – 124.8, $P = 0.004$). The presence of a rotator cuff tear was associated with less reduction of teres minor and deltoid surface-area in patients <50 years, with an effect of a tear of 22mm^2/year (95% confidence interval 1.7 – 41.7, $P = 0.034$) and 250mm^2/year (95% confidence interval 75.8 – 424.3, $P = 0.006$), respectively.

Conclusions: Whereas the surface-area of teres minor and deltoid decrease over time in patient with an intact rotator cuff, the decline in surface-area of these muscles was substantially less in the presence of a rotator cuff tear. Our findings indicate that atrophy may be reduced if an increase in mechanical load is exerted onto the muscle.

INTRODUCTION

Each year up to 30% of the population reports pain, functional deficits and deprived activities of daily living due to shoulder complaints.[25, 28] These complaints are predominantly attributed to conditions affecting rotator cuff (RC) function, including RC tears.[33, 35] Morphologic changes including shoulder muscle size and fatty infiltration have been demonstrated to be an important predictor for long-term shoulder dysfunction during activities of daily living of these patients, which highlights the need for further investigations in determinants affecting muscle size.[11, 29]

Shoulder muscles undergo a continuous decline in muscle mass (i.e. atrophy) as part of an ongoing ageing process throughout adulthood akin to other skeletal muscles.[1, 16, 23, 24, 37] An increase in mechanical loading has been shown to cause changes in muscle architecture and may attenuate this age-associated decline in muscle mass.[6, 9, 23, 27] For that matter, a redistribution of forces in the shoulder suffering from a supraspinatus-tear enlarges mechanical loads of the remaining muscles, which may reduce the usual age-associated decline in muscle mass. The mechanical compensatory increase in muscle activity has been demonstrated in the teres minor and deltoid muscles.[2, 4, 19, 22, 31] Therefore, we postulate that age-associated atrophy of these intact muscles is decelerated in the presence of an RC tear. Current knowledge about atrophic changes that occur in the teres minor and deltoid muscle in the intact RC is based on cross-sectional studies, whereas cohort studies exist for RC tear patients.[1, 17, 22, 24, 26, 37] Consequently, it is unknown whether teres minor or deltoid atrophy can really decelerate or even inverts to muscle hypertrophy in the presence of an RC tear compared to the intact RC, hence an observational cohort study is needed.

The aim of this longitudinal study was to quantify muscle atrophy in two groups of patients: 1) a group with an intact RC and 2) a group with a torn rotator cuff. Data were used to investigate whether atrophy of the teres minor and deltoid muscle in patients with a rotator cuff tear follow a different pattern compared to patients with an intact RC. In agreement with our biomechanical concept of redistribution of forces in RC tears, we hypothesised that the presence of an RC tear is associated with a lower reduction of teres minor and deltoid muscle CSA than in patients with an intact RC.

MATERIALS AND METHODS

Participants

In this retrospective observational cohort study, we evaluated all consecutive patients, who had magnetic resonance imaging (MRI) of the shoulder between January 1, 2005 and March 1, 2014 at the Haaglanden Medical Center, The Hague, the Netherlands. MRI was the principal diagnostic modality to evaluate the RC during the period. Patients with shoulder related complaints and/or functional limitations underwent MRI scanning when intra-articular pathologies (such as an RC tear, labral tear or ligamentous injury) was suspected after medical history and physical evaluation by an orthopaedic trainee or orthopaedic surgeon. Only patients with two MRI scans of the same shoulder with an interval of at least one year between both MRIs were included. Exclusion criteria were: age <30 years, surgical intervention of the RC, MRI artifacts that hampered quantification measurements of muscle size, full-thickness subscapularis tear, fracture, rheumatoid arthritis, muscle dystrophy, tumour and osteonecrosis (Figure 1). In this period, the shoulder of 200 patients had been scanned twice with MRI. Of this group, 129 patients qualified for this study, numbers and reasons for exclusion are presented in Figure 1. The medical ethical committee “Zuidwest Holland” approved this study (14-027) and provided a waiver of the requirement of informed consent.

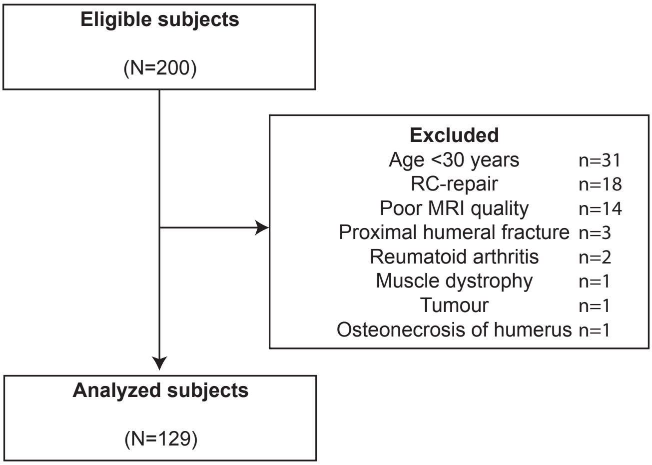

Figure 1. A total of 129 MRIs of the shoulder qualified for evaluation of changes in cross-sectional surface area and were analysed twice. Abbreviations: MRI, magnetic resonance imaging; N, number; RC, rotator cuff.

MR imaging procedure

MRI scans were performed with a dedicated shoulder coil and turbo spin-echo sequences on Avanto or Symphony 1.5T MRI units (Siemens AG, Erlangen, Germany). T1 weighted images (TR/TE 500-600ms /11-15ms, slice thickness 4mm, inter-slice gap 1mm, field of view of 15cm) or T2 weighted images with fat suppression (TR/TE 2240ms/90ms, slice thickness 4mm, inter-slice gap 0.4mm) were used for our systematic evaluation of muscle size [10, 17, 32, 37]. Images were visualized on a picture archiving and communication system and analysed with Sectra IDS5 (Sectra Medical Systems AB, Linköping, Sweden).

Muscle size of the RC and deltoid muscles were quantified by measuring the cross-sectional surface area (CSA) on the MRI of the first visit (baseline) and the second follow-up visit using pre-specified methodology.[10, 14, 17, 26, 32, 37] Good reliability of our methods has been described.[14] In brief, the CSA of supraspinatus, infraspinatus, teres minor and subscapularis were measured in the parasagittal plane on the most lateral slice where the anatomical glenoid neck and base of the coracoid process were present. The CSA of the deltoid muscle was measured in the transverse plane with the humeral head at its widest point. The widest radius of the humeral head was determined by fitting circles onto the humeral head at various slices to calculate its relative size with respect to the population average. Since differences in anthropometrics may exist, the use of normalised CSA (mm^2) has been suggested.[26] We also present the normalised CSA calculated by multiplying the patients' raw CSA and their relative humeral head size. Since the teres minor and deltoid are assumed to experience enlarged mechanical loads in the presence of an RC tear and generally do not tear, we focused on the changes in CSA of these muscles.[2, 4, 19, 22, 31]

Each RC muscle was scored as intact or as torn at both visits (i.e. baseline and follow-up). RC tear geometry was determined by measuring the size of the tear in the sagittal and coronal plane.[5, 14, 34] The maximal sagittal and coronal tear dimension were measured by drawing a straight line in the anterior-to-posterior configuration (i.e. tear width) and by drawing a straight line from the supraspinatus footprint to the medial edge of the tear (i.e. tear length). Using tear dimensions, a massive RC tear was defined as a long and wide tear (both >20mm).[5]

Statistical analyses

Patients were categorised into two groups for plotting our data: the first group (i.e. controls, n=92) had an intact RC at follow-up and the second group (n=37) had an RC tear limited to the supraspinatus or in combination with the infraspinatus tendon at both baseline and follow-up. To obtain sufficient numbers in all groups, we did not further categorise RC tear patients although tear dimension may act differently on shoulder biomechanics. Baseline characteristics were compared using an independent Student's t-test or Pearson chi-square test when appropriate.

A linear mixed model analysis was used to compare the change in normalised CSA between the intact RC and torn RC group per year for each shoulder muscle and its 95% confidence interval (CI). This mixed model analysis enables to deal with the development of an RC tear over time and the covariance of errors in study designs with repeated measurements. A random intercept in combination with an autoregressive structure of order one for the within patient residuals was used to model covariance. The dependent variable was the normalised CSA, measured at baseline and at follow-up. Presence of an RC tear on the MRI-scan (i.e. yes/no), baseline age, sex (male/female), follow-up time (years, interval between baseline and follow-up), and the interaction between the presence of an RC tear and follow-up time in years were included as fixed effects. The interaction term was used to describe the difference in morphologic structural changes over time between patients with and without an RC tear. Because both groups differed in mean age and changes in muscle mass could be different at various decades of life, we performed additional subgroup analyses in patients ≤50 years of age and patients aged >50 years. Subgroup division was arbitrarily set at 50 years to maintain sufficient numbers in each stratum. Statistical analyses were conducted using IBM SPSS statistics for Windows (version 20.0, IBM Corp, 2011, Armonk, New York, USA). A two-sided P value of <0.05 was considered statistically significant.

RESULTS

Demographics

Baseline characteristics of the 129 patients with a baseline and follow-up MRI are described in Table 1. At baseline, 105 patients had an intact RC [i.e. subacromial pain syndrome (n=67), acromioclavicular osteoarthritis (n=16), labral defect (n=15), or ligamentous injury (n=7)]. Twenty-four patients had an RC tear at baseline (i.e. 16 isolated supraspinatus tears and 8 massive posterosuperior RC tears). At follow-up, the RC was still intact in 92 out of 105 subjects (88%). Seven patients had developed an isolated supraspinatus tear, four patients with a supraspinatus tear developed a massive RC tear and six patients with an intact RC at baseline had developed a massive RC tear at follow-up. In total, 37 patients had an RC tear at follow-up (i.e. 19 isolated supraspinatus tears and 18 massive posterosuperior RC tears). Mean follow-up was 3 years in both groups. Mean age in the RC tear group was 11 years (95%CI 7.4 – 14.5, P < 0 .001) higher than the intact RC group.

Table 1. Baseline characteristics

	Intact RC	**RC tear**
	N = 92	N = 37
Age, mean ± SD, yrs	46 ± 9.5	57 ± 8.5
Follow-up, mean ± SD, yrs	3 ± 1.8	3 ± 1.9
Male sex, n (%)	48 (52%)	26 (70%)
Left side studied, n (%)	46 (50%)	16 (43%)
Coronal tear size, mean ± SD, mm	N/A	27 ± 13.1
Sagittal tear size, mean ± SD, mm	N/A	23 ± 12.6

Abbreviations: RC, rotator cuff; N, number; SD, standard deviation; yrs, years; mm, millimetre; N/A, not applicable.

Changes in cross-sectional surface area in the shoulder

Raw data with unadjusted mean CSA of each shoulder muscle is presented in Table 2. In the intact RC group, the mean decrease in size of the teres minor, subscapularis and deltoid was 23mm^2 (95%CI 0.4 – 46.2), 57mm^2 (95%CI 13.0 – 101.5) and 241mm^2 (95%CI 88.2 – 393.4), respectively (Supplement 1). Raw data are also provided for the RC tear group.

Table 2. Mean CSA for individual shoulder muscles

		n	**Intact RC**	*n*	**RC tears**
Supraspinatus CSA, mean ± SD, mm^2					
	Baseline	*92*	418 (102)	*36*	362 (117)
	Follow-up	*92*	414 (108)	*37*	322 (117)
Infraspinatus CSA, mean ± SD, mm^2					
	Baseline	*92*	700 (180)	*37*	659 (232)
	Follow-up	*92*	718 (209)	*37*	652 (247)
Teres minor CSA, mean ± SD, mm^2					
	Baseline	*92*	468 (123)	*37*	450 (139)
	Follow-up	*92*	444 (106)	*37*	462 (169)
Subscapularis CSA, mean ± SD, mm^2					
	Baseline	*92*	668 (243)	*37*	597 (262)
	Follow-up	*90*	608 (241)	*37*	602 (263)
Deltoid CSA, mean ± SD, mm^2					
	Baseline	*79*	3779 (979)	*31*	3995 (1058)
	Follow-up	*87*	3620 (964)	*34*	3864 (880)

Mean CSA on MRI for shoulder muscles at baseline and follow-up stratified on the absence (i.e. intact RC group) or presence (RC tear group) of an RC tear at follow-up at 3 years' follow-up. Abbreviations: RC, rotator cuff; CSA, cross-sectional surface area; mm, millimetre; SD, standard deviation.

Does cross-sectional surface area change differently in patient with a rotator cuff tear versus those with an intact RC?

When incorporating baseline age, sex, differences in interval between two consecutive MRIs and the development of an RC tear over time into our mixed model (i.e. adjusting for these fixed factors), the CSA of the teres minor decreased with 6 mm^2/year in the intact RC group (Table 3). A 10 mm^2/year increase in CSA of the teres minor was found in the RC tear group. The effect of an RC tear was a reduced decline of teres minor CSA with 15mm^2/year (95%CI 3.8 – 27.0, $P = 0.010$ or 3% of its baseline size), resulting in a net yearly growth. We did not find a significant association between an RC tear and the CSA of the deltoid muscle without age stratification. In the subscapularis muscle, the annual decline in CSA was decreased in the presence of an RC tear with 34 mm^2/year (6% of the baseline size) compared to the decline in the control group (Supplement 2).

Subgroup analyses with age stratification showed that in patients younger than 50 years (n=80) atrophy of the teres minor and deltoid follows a different pattern in the intact compared to the torn RC group (Table 3, Figure 2). While there was profound muscle atrophy of the teres minor and deltoid muscle in the young intact RC group, the decline in CSA in younger patients with an RC tear slowed down, with 22mm^2/year (95%CI 1.7 – 41.7, $P = 0.034$) and 250mm^2/year (95%CI 75.8 – 424.3, $P = 0.006$) on total CSA in the presence of an RC tear (Table 3).

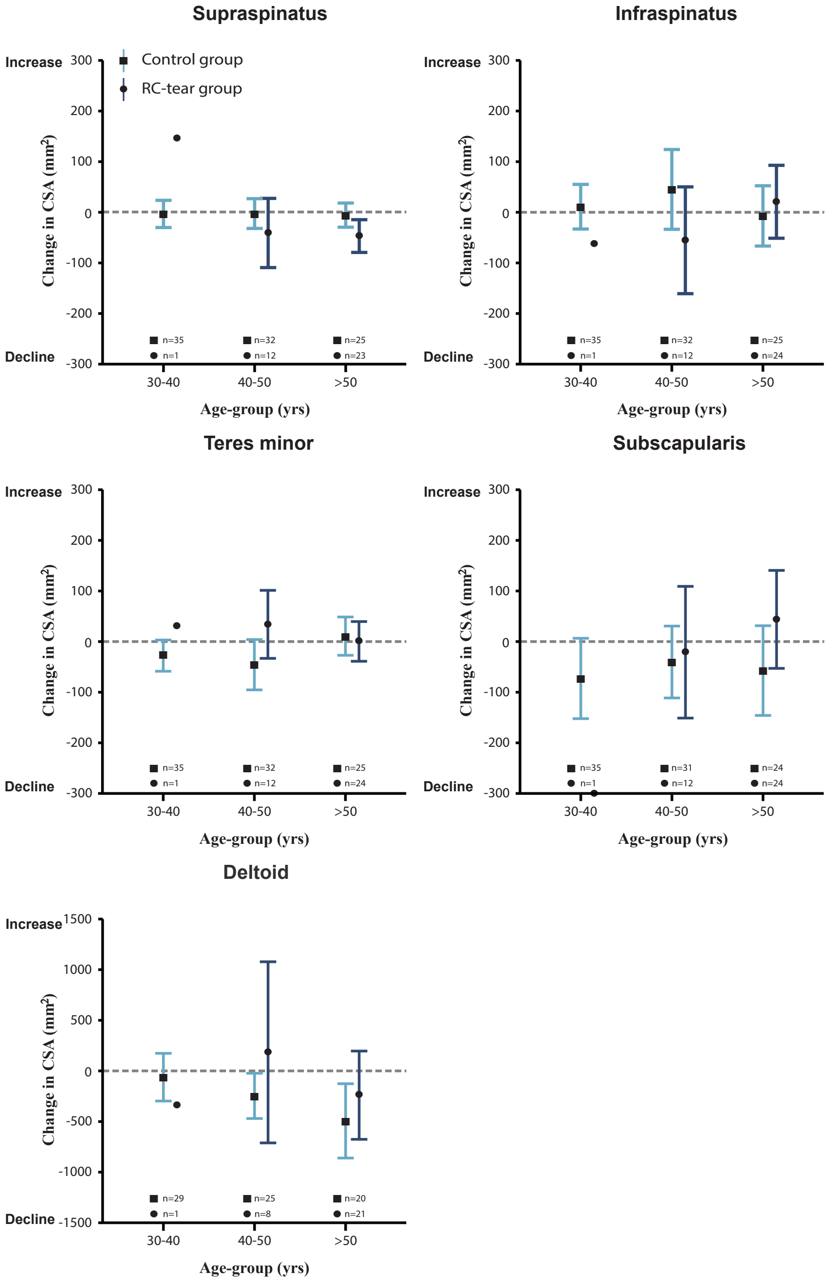

Figure 2. Change in cross-sectional muscle surface area per age category. Mean total change in CSA and 95% confidence interval between MRI measurements for patients with an intact RC (▪, n = 92) and a supraspinatus tear (●, n = 37) at three age categories. Controls and the RC tear group are categorised according to the diagnosis at follow-up. Numbers described the number of available data and may represent missing data. Abbreviations: RC, rotator cuff; CSA, Cross-section surface area; mm, millimetre; yrs., years.

Table 3. Changes in CSA per year of the teres minor and deltoid muscle

	Teres minor CSA (mm^2/yr)		Deltoid CSA (mm^2/yr)	
	Mean change (95% CI)	*p value*	Mean change (95% CI)	*p value*
≤ 50 years				
Model for intact RC[a]	-9 (-16.1 – -2.7)	0.007[*]	-49 (-104.5 – 6.1)	0.080
Model for RC tear[a]	12 (-6.4 – 31.1)	0.196	201 (36.0 – 365.7)	0.018[*]
Fixed effect: RC tear	22 (1.7 – 41.7)	0.034[*]	250 (75.8 – 424.3)	0.006[*]
> 50 years				
Model for intact RC[a]	1 (-6.5 – 9.4)	0.718	-123 (-214.9 – -23.0)	0.010[*]
Model for RC tear[a]	8 (-3.3 – 19.7)	0.159	-81 (-200.3 – 39.2)	0.184
Fixed effect: RC tear	7 (-7.5 – 21.0)	0.346	42 (-109.3 – 195.1)	0.575
All patients				
Model for intact RC[a]	-6 (-11.1 – -0.7)	0.026[*]	-75 (-124.8 – -24.5)	0.004[*]
Model for RC tear[a]	10 (-0.7 – 19.7)	0.068	-19 (-113.5 – 76.4)	0.700
Fixed effect: RC tear	15 (3.8 – 27.0)	0.010[*]	56 (-51.8 – 164.0)	0.306

A decline in CSA is indicated with a minus sign (-). Mixed model analysis enables to deal with the development of an RC tear over time and to adjust for age, sex and differences in interval between two consecutive MRIs. Abbreviations: CSA, cross-sectional surface area; mm^2/yr, square millimetre per year, year CI, confidence interval; RC, rotator cuff.

[*] Statistically significant difference at $P < 0.05$

[†] Mixed model with fixed effects: presence of an RC tear on MRI (yes/no), age (years), sex (male/female), follow-up time in years, presence of an RC tear x follow-up time in years, and a random intercept for subjects.

DISCUSSION

This longitudinal study showed that progressive muscle atrophy of teres minor and deltoid was present in shoulders with an intact RC, but this decline in CSA was unnoticed in case of an RC tear. In patients with a supraspinatus tear, the decline in CSA of non-torn teres minor and deltoid muscle slowed down and an increase in mean muscle CSA was found at follow-up, which was most prominent in the stratified 50 years and younger group.

Our findings in patients with an RC tear are in agreement with cross-sectional data from prior studies.[1, 17, 24, 26, 37] Nevertheless, prior cross-sectional studies were not designed to analyse muscular changes within a single patient over time. Muscular changes in a single patient have been investigated in patients with a supraspinatus tear that underwent surgical repair, with conflicting effects on muscle atrophy.[8, 11, 12, 18, 21] While some authors claimed that atrophic changes are irreversible in RC tears, others claimed reversibility of atrophy after successful tendon reinsertion.[8, 11, 12, 18, 21] The latter suggests that restored mechanical load may induce muscle hypertrophy or growth and may interfere with age-dominated atrophy. Mechanical load has been shown to prompt changes in muscular architecture, even in the elderly.[6, 9, 23, 27] On the contrary, age-associated muscle atrophy should not be excluded as a factor contributing to the development of RC tears, since contractile tissue of the muscle has an undeniable effect on alignment of fibres and function of the tendon.[6, 23] Our data, with an age-associated decline in CSA in intact muscles, suggests that atrophic changes in RC tear patients (partly) reflect an ageing phenomenon. Chung et al. underlined this importance of age-associated atrophy by demonstrating a lower sarcopenic index in patients with an RC tear than controls.[3]

A reduced decline of teres minor CSA in the presence of an RC tear is in line with the results from several cross-sectional studies.[17, 22]. They found hypertrophic changes in the teres minor of patients suffering from an RC tear.[17, 22] Hypertrophy of the teres minor has also been observed after detachment of the RC in rats.[15] A supraspinatus tear causes a shift of glenohumeral forces towards the remaining teres minor, subscapularis and deltoid muscle.[13, 19, 31] It has been demonstrated that the forces generated by the teres minor are crucial to maintain a stable fulcrum for shoulder motion, especially when the infraspinatus muscle is unable to provide a sufficient amount of glenohumeral torque.[13, 19, 31] Like the teres minor, the deltoid muscle compensates for lost torques in RC tears to preserve sufficient torques for elevation of the arm.[7, 13, 20, 31] Mechanical loading of muscles may induce muscle growth resulting in an increase in CSA of the teres minor within RC tear patients, especially in younger patients as indicated by our results in patients < 50 years of age, due to an age-associated capacity for muscle growth.

RC atrophy is an essential predictor for proximal migration of the humerus and shoulder function in RC tears.[11, 12, 14] The increase in CSA of the teres minor and deltoid size in RC tears suggests that altered mechanical load in the shoulder with a supraspinatus tear is counteracted by natural mechanical compensation. The biomechanical importance of the teres minor is also stressed by the superior functional results in reversed total shoulder arthroplasty in patients with an unaffected teres minor.[2, 4, 30] Improved knowledge of dynamic adaptations of intact RC and deltoid muscles in the presence of an RC tear may contribute to the development of novel prognostic determinants and optimization of rehabilitation strategies to train muscles before or following RC repair or shoulder arthroplasty.

This study does have several limitations. Firstly, patients with persistent shoulder complaints are more likely to undergo imaging twice that may lead to forced selection. Because changes of the teres minor and deltoid muscles are assumed favourable biomechanical compensation for lost RC forces, a more noticeable increase in muscle size could be expected in RC tear patients without follow-up due to relieve of pain. Secondly, slight variations in imagined plane on MRI due to cranial translation (i.e. for deltoid) or tendon retraction may impair validity, although semi-quantitative CSA measurements have been shown to be reliable and are frequently applied [1, 14, 22, 37], recent studies question its association with three-dimensional muscle architecture.[36] We chose CSA as a measure for muscle mass, though it measures intra-muscular connective tissue and fat as well leading to an overestimation of contractile tissue.[23] Finally, we assumed a similar development of muscle CSA in all patients with an intact RC, although these patients may suffer from different shoulder pathologies. Thus, changes in muscle mass in these shoulders may deviate from changes in an asymptomatic shoulder.

CONCLUSION

This longitudinal study demonstrated that the size of teres minor, subscapularis and deltoid muscle decrease over time in the absence of an RC tears. Whereas the CSA of teres minor and deltoid decreases over time in patients with an intact RC, the decline in CSA of these muscles was substantially less in the presence of a supraspinatus tear. This association was most prominently found in the population below 50 years of age. These findings may indicate that intact shoulder muscles may compensate for shifts of forces up to midlife and suggests that atrophy is decreased by compensatory enlargement of mechanical load.

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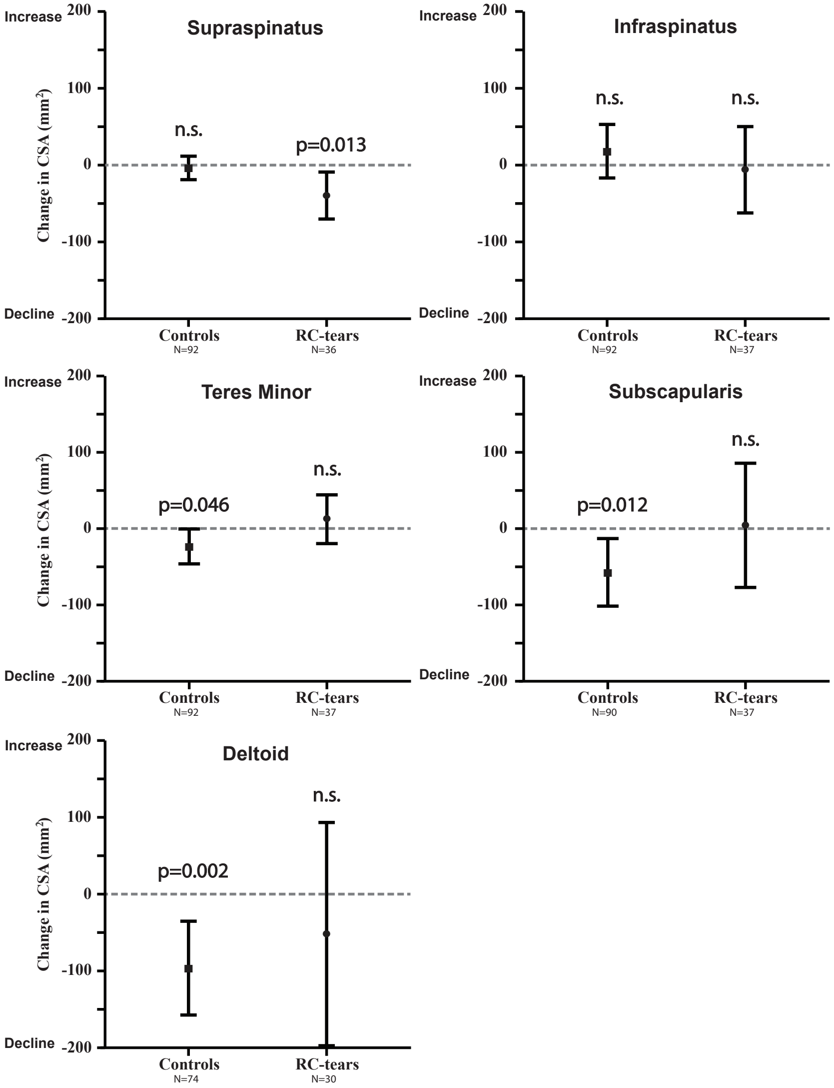
Supplement 1. Mean difference in cross-sectional surface area.



(CSA) between baseline and follow-up and 95% confidence interval for the control group with an intact RC (▪, n=92), and with a supraspinatus-tear (●, n=37) with a mean follow-up of 3 years. Abbreviations: RC, rotator cuff; mm, millimetre.

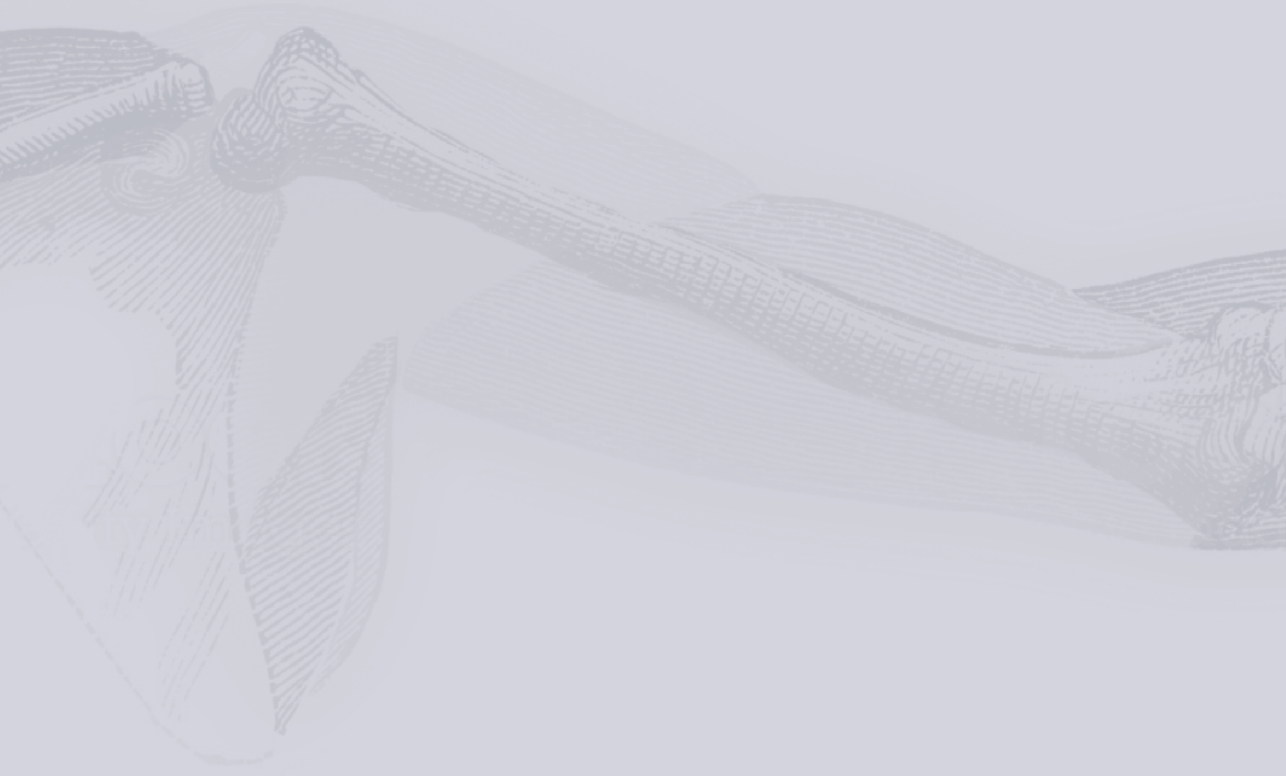
Supplement 2. Changes in CSA per year during follow-up

	Supraspinatus CSA (mm^2/yr)		Infraspinatus CSA (mm^2/yr)		Subscapularis CSA (mm^2/yr)	
	Mean change (95% CI)	P value	Mean change (95% CI)	P value	Mean change (95% CI)	P value
≤ 50 years						
Model for intact RC[a]	-1 (-7.8 – 5.4)	0.720	11 (-2.7 – 23.9)	0.118	-12 (-28.1 – 4.9)	0.163
Model for RC tear[a]	-2 (-19.3 – 14.4)	0.771	1 (-32.9 – 34.6)	0.960	-9 (-50.0 – 31.7)	0.655
Fixed effect: RC tear	-1 (-19.4 – 16.8)	0.888	-10 (-46.0 – 26.6)	0.596	2 (-41.7 – 46.6)	0.912
> 50 years						
Model for intact RC[a]	-1 (-7.1 – 4.9)	0.720	-0 (-14.8 – 14.2)	0.968	-11 (-31.9 – 9.7)	0.287
Model for RC tear[a]	-3 (-11.5 – 6.0)	0.531	19 (-1.4 – 39.0)	0.068	37 (9.1 – 65.5)	0.010[*]
Fixed effect: RC tear	-2 (-12.5 – 9.1)	0.758	19 (-6.3 – 44.5)	0.138	48 (12.8 – 84.1)	0.009[*]
All patients						
Model for intact RC[a]	-1 (-5.9 – 3.7)	0.647	7 (-2.7 – 16.9)	0.155	-11 (-23.3 – 1.2)	0.076
Model for RC tear[a]	-2 (-11.3 – 6.5)	0.594	11 (-7.6 – 28.9)	0.250	22 (-0.1 – 45.0)	0.051
Fixed effect: RC tear	-1 (-11.5 – 8.9)	0.801	4 (-17.3 – 24.5)	0.736	34 (7.6 – 59.5)	0.012[*]

Minus (-) indicates a decline in cross-sectional surface area. Mixed model analysis enables to deal with the development of an RC tear over time and to adjust for age, sex, differences in interval between two consecutive MRIs. Abbreviations: CSA, cross-sectional surface area; mm^2/yr, square millimetre per year, year CI, confidence interval; RC, rotator cuff.

[*] Statistically significant difference at $P < 0.05$.

[†] Mixed model with fixed effects: presence of an RC tear on MRI (yes/no), age (years), sex (male/female), follow-up time in years, presence of an RC tear x follow-up time in years, and a random intercept for subjects.



7

Three-dimensional shoulder kinematics normalise after rotator cuff repair

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ABSTRACT

Background: Patients with a rotator cuff tear often exhibit scapular dyskinesia with increased scapular lateral rotation and decreased glenohumeral elevation with arm abduction. We hypothesised that in patients with a rotator cuff tear, scapular lateral rotation, and thus glenohumeral elevation, will be restored to normal after rotator cuff repair.

Methods: Shoulder kinematics were quantitatively analysed in 26 patients with an electromagnetic tracking device (Flock of Birds) before and one year after rotator cuff repair in this observational case series. We focused on humeral range of motion and scapular kinematics during abduction. The asymptomatic contralateral shoulder was used as the control. Changes in scapular kinematics were associated with the gain in range of motion. Shoulder kinematics were analysed using a linear mixed model.

Results: Mean arm abduction and forward flexion improved after surgery with 20° (95% confidence interval 2.7° – 36.5°, P = 0.025) and 13° (95% confidence interval 1.2° – 25.5°, P = 0.044), respectively. Kinematical analyses showed decreases in mean scapular internal rotation (i.e. protraction) and lateral rotation (i.e. upward rotation) during abduction with 3° (95% confidence interval 0.0° – 5.2°, P = 0.046) and 4° (95% confidence interval 1.6° – 8.4°, P = 0.042), respectively. Glenohumeral elevation increased with 5° (95% confidence interval 0.6° – 9.7°, P = 0.028) at 80°. Humeral range of motion increased when scapular lateral rotation decreased and posterior tilt increased.

Conclusions: Scapular kinematics normalise after rotator cuff repair towards a symmetrical scapular motion pattern as observed in the asymptomatic contralateral shoulder. The observed changes in scapular kinematics are associated with an increased overall range of motion and suggest restored function of shoulder muscles.

INTRODUCTION

Rotator cuff (RC) tears have a prevalence ranging from 20% to 50% in the general population and frequently lead to pain, deficits in shoulder function, and deprived quality of life.[26, 34] If conservative treatment (e.g. nonsteroidal anti-inflammatory drugs and physiotherapy) fails, surgical repair of the RC is a widely used therapeutic option. The number of RC repairs has increased over the past decade because the procedure is generally considered to relieve pain and to effectively restore shoulder function.[6, 21, 29]

Healthy shoulder function depends on a perfect balance between arm mobility and glenohumeral stability.[30] In patients with a full-thickness RC tear, the balance is disrupted because the affected RC muscle is incapable of exerting sufficient forces on the humerus. As a result, deltoid muscle activity increases to compensate for lost RC forces; this in turn, will cause additional cranially directed forces on the humerus.[4, 14, 27] These forces pull the humerus in a more cranial position relative to the glenoid, introducing translation within the glenohumeral joint.[3, 7] Clinically, lost RC muscle functionality coincides with pain and reduced elevation of the arm. It has been postulated that lost glenohumeral motion is generally compensated for by an increase in scapular lateral rotation.[13, 15] The latter is clinically observed in patients with an RC tear as asymmetry of scapular motion with increased scapulothoracic lateral rotation of the affected side.[13, 15, 23, 28]

Theoretically, RC repair should increase glenohumeral elevation because of the restored insertion of the tendinous part of the RC muscles with subsequent normalization of forces and glenohumeral moment. Observation of shoulder motion before and after RC repair may partly elucidate the observed functional gain. Shoulder motion can be measured quantitatively with six degrees of freedom by a three-dimensional (3D) electromagnetic system.[1, 9, 10, 12, 16, 19, 31] However, evaluations of preoperative and postoperative 3D shoulder motion in RC repair with an electromagnetic system have not been published so far. The purpose of this study is to assess 3D shoulder motions in patients before and after RC repair. We hypothesise that after an RC repair, arm elevation increases, glenohumeral elevation increases, and scapular lateral rotation decreases. Thus, scapulothoracic kinematics normalise towards the scapular motion of the asymptomatic contralateral shoulder.

MATERIALS AND METHODS

Participants

From March 2010 to April 2011 patients scheduled for RC repair at a secondary referral centre (Medical Centre Haaglanden, the Hague, the Netherlands) were evaluated for eligibility in this observational case series.

Patients with complaints of a repairable degenerative full-thickness supraspinatus RC tear or full-thickness supraspinatus and infraspinatus RC tear were included. The RC tear was confirmed with magnetic resonance arthrography or computed topography arthrography. The exclusion criteria were cervical radiculopathy, glenohumeral instability, history of a fracture in the shoulder region, muscle dystrophy, glenohumeral or symptomatic acromioclavicular osteoarthritis, rheumatoid arthritis, previous surgery on the shoulder, restriction in passive shoulder motion (i.e. frozen shoulder), and insufficient Dutch-language skills. In addition, patients with bilateral shoulder complaints were excluded.

Patients with an RC tear were invited to the Laboratory of Kinematics and Neuromechanics (Leiden University Medical Centre, Leiden, the Netherlands) for three-dimensional (3D) electromagnetic motion analysis, clinical evaluation including the Western Ontario Rotator Cuff (WORC) index, and assessment of shoulder muscle activity.[8] The assessment of muscle activity has been previously reported.[4] One year after surgery, participants were invited to undergo a follow-up visit. Thirty-eight patients with an RC tear were eligible for the assessment of shoulder kinematics. Patients who underwent preoperative and postoperative motion analysis were included in the analysis (n=26). Twelve patients were excluded from analysis because of a technical error (n=3) or missing baseline measurements (n=9). Ultrasound was used to evaluate RC integrity after the conducted RC repair. The medical ethical review board approved this study (07.116, P10.026) and written informed consent was obtained from every participating individual.

Surgical procedure

All surgical procedures were performed at the Medical Centre Haaglanden by one of two orthopaedic surgeons (ERAvA, PvdZ) with extensive experience in the field of RC repair, the Hague. Either a mini-open or arthroscopic surgical approach was performed according to the surgeon's personal preference. All patients received general anaesthesia and were placed in a lateral decubitus position. The RC was inspected, and the tear was debrided. A bleeding surface was created at the insertion site on the supraspinatus footprint. The RC was repaired using a double-row suture bridge technique. One or two 5.5-mm Corkscrew anchors (Arthrex, Naples, Florida, USA) were used for the medial row depending on the size of the RC tear. Similarly, one or two 3.5-mm knotless Bio-PushLock anchors (Arthrex, Naples, Florida, USA) were used for the lateral row. Postoperatively the arm was placed in an immobilizing arm sling. Patients followed a standardized rehabilitation protocol under the supervision of a physiotherapist. The physiotherapist supervised active abduction exercises. Abduction was limited to 70° during the first 4 to 6 weeks. No external rotation was allowed during this period. After 6 weeks, more active shoulder movements were permitted and isometric strengthening exercises were started.

Electromagnetic motion analysis

Preoperative and postoperative shoulder motion was captured using the Flock of Birds (FoB) (Ascension Technology Inc., Milton, Vermont, USA), which is a 3D electromagnetic motion analysis system. This electromagnetic system is used to quantify shoulder motion and has been shown to be accurate, valid and reliable.[1, 16-20, 24]

The positions and orientations of eight wired sensors were recorded with six degrees of freedom using an electromagnetic field generated by an extended-range transmitter. The sampling rate of the sensors was about 30Hz. The investigator attached seven sensors in a standardized way to the sitting patient.[1, 17] Adhesive tape was used to attach a thoracic sensor and two scapular sensors. The thoracic sensor was mounted on the manubrium sterni. The scapular sensors were bilaterally adhered to the flat craniolateral surface of the acromion. Straps with hook-and-loop fasteners were used to position two distal humeral sensors on the posterior flat surface of the distal upper arm. Two distal forearm sensors were positioned on the dorsal side of the distal forearm. Twenty-four bony landmarks were palpated as recommended by the International Society of Biomechanics[32]. Subsequently, the bony landmarks were digitized using a sensor with a known stylus vector[16]. The palpated and digitized bony landmarks were used to define a local Cartesian right-handed coordinate system to construct a patient specific 3D bone model relative to the seven sensors.

After providing verbal and visual instructions, the investigator requested that the patient perform the following bilateral arm movements: abduction (i.e. elevation in the coronal plane), forward flexion, backward flexion (i.e. extension) and external axial rotation with at least 40° of humeral elevation and with the elbow flexed 90°. Forward flexion, backward flexion and external rotation were used only for evaluation of range of motion, and not for comparisons of scapulothoracic rhythm.

Data processing

The constructed local coordinate systems consisted of an anteriorly (X_t), superiorly (Y_t) and laterally (Z_t) directed axes. The orientation of each local coordinate system was related to the coordinate system of the thorax. The motions were described by a defined sequence of three rotations.[32] An Euler sequence (y-x-y) was applied to describe humeral motion: 1) plane of elevation, that is rotation around thoracic y-axis; 2) humerus elevation, that is negative rotation around humeral x'-axis; and 3) humerus external rotation, that is negative rotation around the humeral y''-axis. The Cardan sequence (y-x-z) was applied to describe scapular motion: 1) internal rotation (i.e. protraction), that is positive rotation around the thoracic y-axis; 2) lateral rotation (i.e. upward rotation), that is negative rotation around the scapular x'-axis; and 3) posterior tilt, that is positive rotation around the scapular z''-axis. In contrast to Wu et al., we express humeral elevation, external rotation and scapulothoracic lateral rotation in this study as positive rotations.[32] Comparable to scapulothoracic motion, glenohumeral motion was calculated using a Cardan sequence. Glenohumeral elevation was expressed as a positive rotation. Custom-made MATLAB software (2013b release, The MathWorks Inc., Natick, Massachusetts, USA) was applied to process the data.

Maximal humeral elevation (i.e. range of motion) was evaluated for abduction, forward flexion, backward flexion, and external rotation. Scapulothoracic motion was calculated for abduction in the frontal plane. The mean scapular positions were calculated at standardized humeral elevation angles with intervals of 10° up to 110°. As a consequence of skin movement artifacts in overhead arm positions, we did not analyse scapulothoracic and glenohumeral rotations over 110° of humerothoracic elevation[1]. Because movements were not guided, deviations of the (abduction) plane of elevation exceeding 30° were identified and these data were excluded from the analysis.

Preoperative scapulothoracic and glenohumeral rotations during abduction were analysed and compared with postoperative rotations. Kinematics were assessed in the affected shoulder, as well as in the asymptomatic contralateral shoulder, to assess the symmetry of shoulder kinematics. “Normalization” of shoulder motion was defined as changed kinematics towards symmetrical bilateral scapular motion as it is clinically used to identify scapula dyskinesis.[28] The asymptomatic contralateral shoulder was used as reference.

Statistical analysis

The statistical analysis was conducted using IBM SPSS statistics for Windows (version 20.0, IBM Corp, 2011, Armonk, New York, USA). Normally distributed continuous data were expressed as means and 95% confidence intervals (CIs) and categorical data were expressed by numbers with percentages. A paired Student’s t-test was used to compare the preoperative versus postoperative WORC scores and maximum humerothoracic range of motion in the operated arm for abduction, forward flexion, backward flexion, and external rotation.

Linear mixed model analysis was used for pair-wise scapulothoracic motion comparisons during arm abduction. The dependent variable was the paired difference between the preoperative and postoperative scapular internal rotation, between the preoperative and postoperative lateral rotation, and between the preoperative and postoperative tilt. The paired difference was calculated by subtracting the postoperative from the preoperative scapular rotations in both the affected and contralateral unaffected shoulders. Abduction intervals were included as a repeated factor per subject. The abduction interval and the appearance of a retear were both included as fixed effects. An autoregressive structure of order one with unequal variances was used to model the covariance at the various time points. An autoregressive structure of order one was used if convergence was not achieved. Even though the preoperative and postoperative data were collected in a similar way, small differences in the plane of elevation or axial rotation may occur when asking the patients to perform an abduction movement twice. Therefore, the humeral plane of elevation and axial rotation were initially included in the model as covariates, but they did not lead to a different conclusion and were excluded from the presented results.

A forced-entry linear regression analysis was performed to evaluate the correlation between range of motion and scapular rotations. For every 10° of humeral elevation, changes in the scapular internal rotation, lateral rotation and posterior tilt were used as independent variables and the change in humeral range of motion during abduction as the dependent variable. A correlation coefficient of < 0.3 was considered as poor, 0.3 to 0.5 as fair; 0.5 to 0.8 as moderate to good and >0.8 as very strong. A two-sided P value of < 0.05 was considered statistically significant.

RESULTS

Clinical characteristics

The twenty-six patients comprised 17 men and 9 women, with a mean age of 60 years (range, 46 – 73 years). Fifteen patients with a supraspinatus tear and eleven patients with a combined tear of the supraspinatus and infraspinatus were included. The median follow-up was 13 months (interquartile range, 1.6 months; range 12 – 17 months). The characteristics of these twenty-six patients are presented in Table 1.

Table 1. Baseline characteristics

	N=26	
Age, yrs	60	(46.4-72.7) †
Female, n (%)	9	(35)
Left side affected, n (%)	15	(58)
Traumatic origin, n (%)	8	(31)
Coronal tear size, mm	23	(19.1-27.2) †
Sagittal tear size, mm	20	(16.4-23.9) †
Posterosuperior tear, n (%)	11	(42)
Fatty infiltration supraspinatus, n (%)		
Stage 0	11	(42)
Stage 1	10	(39)
Stage 2	5	(19)
Arthroscopic repair, n (%)	17	(65)
Biceps tenotomy, n (%)	8	(31)
Retear, n (%)	6	(23)
Constant Score, points	52	(45.3-58.7) †
WORC, %		
Baseline	44	(34.7-53.9) †
Follow-up (1yr)	68	(58.2-78.2) † *

We observed a significant increase in WORC percentage. Preoperative and postoperative WORC score was compared using the paired Student's T-test. Abbreviations: yrs, years; mm, millimetre; WORC, Western Ontario Rotator Cuff Index.

* statistically significant difference from baseline at $P < 0.05$.

† mean and 95% confidence interval.

The postoperative WORC score improved significantly with 24 percentage points (95%CI 16.3 – 31.5, P < 0.001). One subject did not complete the WORC. Postoperative range of motion significantly increased with 20° for abduction and with 13° for forward flexion (Table 2).

Table 2. Humeral range of motion before and after rotator cuff repair

	Pre-operative Range of motion *(N = 26)*	Post-operative Range of motion *(N = 26)*	Mean difference	
	Mean (SD) °	Mean (SD), °	(95% CI), °	P value
Abduction (°)	118 (37.3)	138 (20.0)	20 (2.7 – 36.5)	0.025*
Forward flexion (°)	127 (31.4)	140 (15.6)	13 (1.2 – 25.5)	0.044*
Backward flexion† (°)	53 (12.0)	55 (12.4)	3 (-1.7 – 6.8)	0.223
External rotation (°)	69 (19.9)	75 (17.9)	6 (-1.3 – 13.2)	0.102

After rotator cuff repair, the investigated patients showed more abduction and more forward flexion. Abbreviations: n, number; SD, standard deviation; CI, confidence interval.

* statistically significant difference at P < 0.05.

† i.e. extension.

Shoulder kinematics during abduction

Kinematics of the unaffected shoulder before and after surgery.

In the asymptomatic contralateral shoulders, no differences were observed in scapular motion before versus after surgery. On the bases of averaged differences over the analysed range of motion (up to 110°) scapulothoracic kinematics in the unaffected shoulder did not significantly change: -1° (95%CI -4.4° – 3.4°, P = 0.787) for scapulothoracic internal rotation, -2° (95%CI -4.5° – 1.1°, P = 0.223) for lateral rotation, and -1° (95%CI -3.6° – 2.2°, P = 0.617) for posterior tilt.

Kinematics of the affected shoulder before and after surgery.

Scapulothoracic rotations changed in the affected shoulder towards the motion patterns as observed in the contralateral asymptomatic shoulder, indicating a more symmetrical movement pattern after RC repair (Figure 1). In the operated shoulders, mean postoperative scapular internal rotation (i.e. protraction) decreased with 3° (95%CI 0.0° – 5.2°, P = 0.046). The preoperative internal rotation was 3° to 4° higher from 20° to 70° of abduction than the postoperative scapular internal rotation (Table 3). Mean postoperative scapular lateral rotation (i.e. upward rotation) in all intervals was reduced with 4° (95%CI 1.6° – 8.4°, P = 0.042). This difference in scapular lateral rotation in the affected shoulder was demonstrated to be ± 5° at 80° – 90° abduction. Scapular posterior tilt in the affected shoulder was, on average 2° (95%CI 0.5° – 5.3°, P = 0.097) higher after surgery, but this difference did not reach significance.

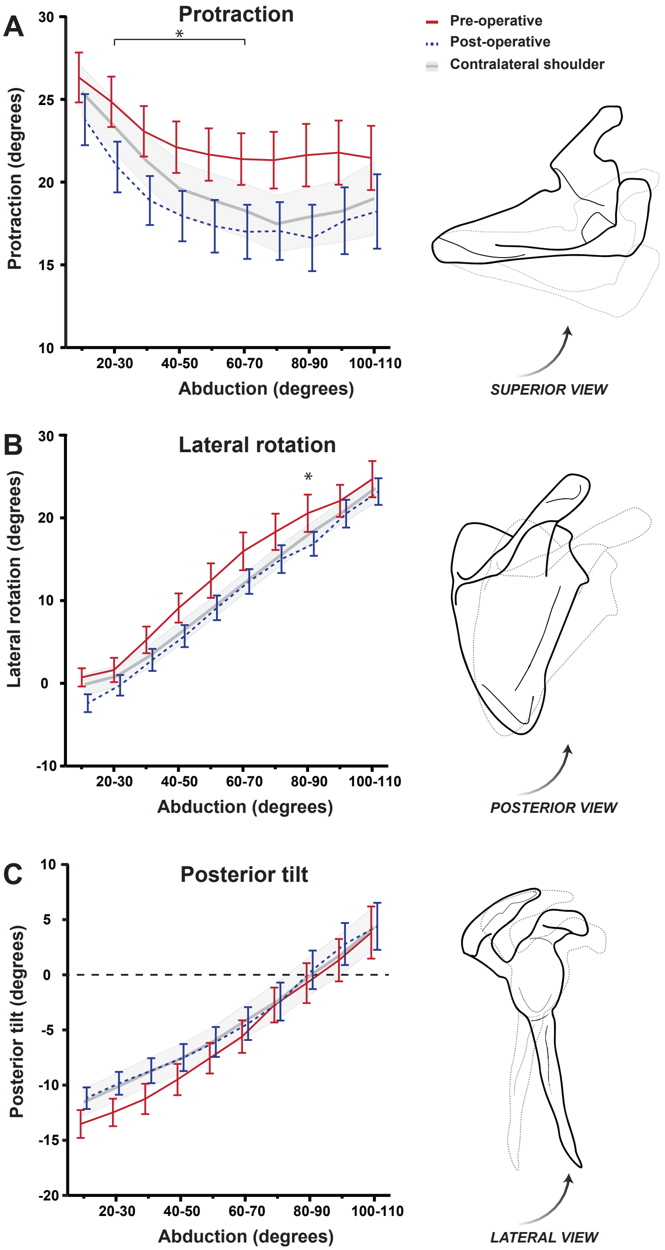

Figure 1. Scapulothoracic movements showing A) protraction, B) lateral rotation, and C) posterior tilt. Data are presented as mean and ± 1 standard error. The data were analysed by pair-wise linear mixed model analysis. Preoperative (solid, red line) scapulothoracic protraction and lateral rotation were significantly higher compared with the postoperative state (dotted, blue line). The postoperative results were comparable to the shoulder movements observed in the symptom-free contralateral shoulder (reference, grey line). This finding indicates a normalization of shoulder kinematics after rotator cuff repair.

* statistically significant difference at $P < 0.05$.

Table 3. Difference between preoperative and postoperative scapulothoracic rotations

Protraction				
	N	Mean change, °	95% CI	P value
10-20°	25	-3	-5.4 – 0.2	0.063
20-30°	26	-4	-6.8 – -1.3	0.005*
30-40°	25	-4	-6.4 – -1.3	0.004*
40-50°	24	-4	-6.0 – -1.0	0.008*
50-60°	23	-3	-5.7 – -0.8	0.012*
60-70°	22	-3	-5.5 – -0.3	0.028*
70-80°	20	-3	-5.1 – 0.1	0.059
80-90°	17	-3	-5.5 – 0.1	0.055
90-100°	16	-2	-5.2 – 0.8	0.144
100-110°	13	-1	-3.9 – 2.5	0.652
Retear		0	-2.5 – 3.4	0.760
Lateral rotation				
	N	Mean change, °	95% CI	P value
10-20°	25	-3	-5.6 – 0.6	0.110
20-30°	26	-2	-5.1 – 2.2	0.424
30-40°	25	-2	-5.9 – 1.9	0.296
40-50°	24	-3	-7.5 – 1.1	0.141
50-60°	23	-3	-8.0 – 1.4	0.165
60-70°	22	-4	-9.4 – 0.8	0.097
70-80°	20	-4	-8.9 – 0.4	0.069
80-90°	17	-5	-9.3 – -0.3	0.049*
90-100°	16	-3	-7.8 – 1.2	0.142
100-110°	13	-3	-7.6 – 0.9	0.116
Retear		-2	-5.9 – 1.7	0.284
Posterior tilt				
	N	Mean change, °	95% CI	P value
10-20°	25	2	-0.4 – 4.8	0.095
20-30°	26	2	-0.1 – 4.9	0.054
30-40°	25	3	-0.3 – 5.2	0.076
40-50°	24	2	-0.7 – 5.1	0.130
50-60°	23	2	-1.1 – 4.8	0.209
60-70°	22	2	-1.3 – 4.7	0.263
70-80°	20	1	-1.7 – 4.2	0.385
80-90°	17	1	-1.8 – 4.6	0.372
90-100°	16	2	-1.3 – 5.6	0.208
100-110°	13	1	-2.7 – 4.5	0.602
Retear		1	-1.7 – 3.8	0.439

The difference between preoperative and postoperative scapulothoracic protraction and lateral rotation significantly changed over the various humerothoracic abduction intervals. The presented main effects indicate the difference in degrees at the specific abduction intervals. Abbreviations: n, number; 95% CI, 95% confidence interval.

* statistically significant difference at $P < 0.05$.

The reduction of scapulothoracic rotation stratified for humeral elevation indicated an increase in glenohumeral elevation. Indeed, more glenohumeral elevation (5°; 95%CI 0.6° – 9.7°, P = 0.028) was postoperatively shown in the operated shoulder at 80° to 90° of abduction (Figure 2).

In 6 of 26 patients, we observed a retear. Subgroup analysis, however, showed no significant differences in preoperative and postoperative kinematics between patients with a retear versus patients with an intact cuff with respect to internal rotation (0°; 95%CI -2.5° – 3.4°], P = 0.760), lateral rotation (-2°; 95%CI -2.9° – 1.7°, P = 0.284), and tilt (1°; 95%CI -1.7° – 3.8°, P = 0.439).

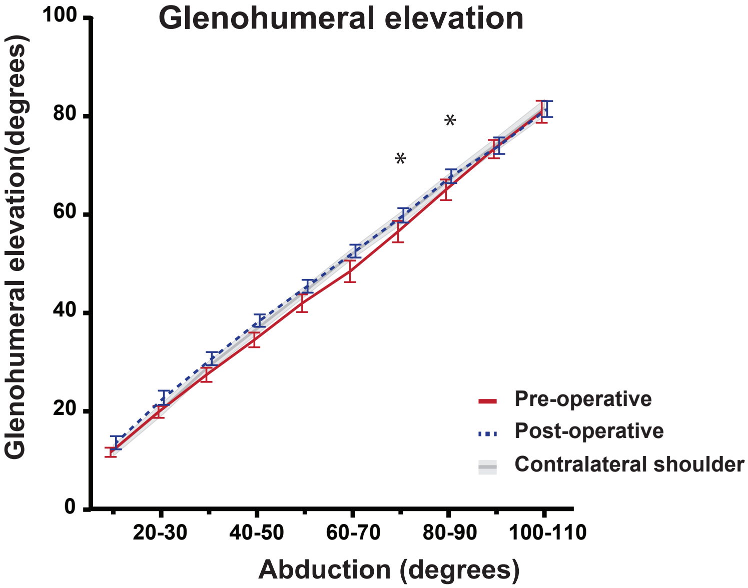

Figure 2. Data are presented as mean and ± one standard error. After rotator cuff repair, the glenohumeral contribution to elevation increased and normalised to the motion observed in the asymptomatic shoulder. This finding is consistent with the changes in scapulothoracic lateral rotation.

* statistically significant difference at $P < 0.05$.

Scapulothoracic rotations during abduction are correlated with range of motion

There was a moderate to good correlation between change in scapulothoracic motion and the increase in range of motion (i.e. maximal elevation angles) during an abduction movement (Table 4). The humeral range of motion increased by 1° for every 1.6° – 1.9° decrease in scapular lateral rotation at 20° to 60° abduction. The humeral range of motion increased by 1° for every 2.0° – 3.8° increase in posterior tilt.

Table 4. Scapulothoracic movements correlates with maximal range of motion

Humero-thoracic abduction	*R*	*P value*		*B*	*95% CI*	*P value*
10-20°	0.560	0.044*	protraction	-1.2	-3.74 – 1.34	0.337
			lateral rotation	-1.3	-3.79 – 1.25	0.307
			posterior tilt	3.8	1.11 – 6.40	0.008*
20-30°	0.633	0.009*	protraction	-0.8	-3.10 – 1.51	0.482
			lateral rotation	-1.9	-3.74 – -0.02	0.048*
			posterior tilt	3.8	1.30 – 6.28	0.005*
30-40°	0.674	0.005*	protraction	-0.5	-2.97 – 1.98	0.681
			lateral rotation	-1.9	-3.55 – -1.20	0.030*
			posterior tilt	3.4	1.14 – 5.58	0.005*
40-50°	0.702	0.003*	protraction	-0.5	-13.26 – 19.68	0.666
			lateral rotation	-1.9	-3.26 – -0.63	0.009*
			posterior tilt	2.6	0.73 – 4.55	0.006*
50-60°	0.669	0.009*	protraction	-0.1	-9.43 – 19.69	0.893
			lateral rotation	-1.6	-2.66 – -0.44	0.009*
			posterior tilt	2.0	0.17 – 3.92	0.034*
60-70°	0.739	0.002*	protraction	0.0	-1.89 – 1.94	0.978
			lateral rotation	-1.7	-2.65 – -0.85	0.001*
			posterior tilt	1.6	-0.17 – 3.34	0.074

Results of forced entry linear regression analysis with maximal range of motion during abduction as dependent variable and scapular rotations as independent variable. Because the number of scapulothoracic rotation observations decreased, because of elimination of more seriously affected patients, data were analysed until 70° of humerothoracic abduction. Abbreviations: R, correlation coefficient; B, estimate; CI, confidence interval.

* statistically significant difference at $P < 0.05$.

DISCUSSION

This study aimed to assess 3D shoulder motion in patients with an RC tear and to evaluate whether scapulothoracic and glenohumeral elevation normalises after surgical RC repair. Scapulothoracic internal rotation and lateral rotation in patients with an RC tear decreased significantly and normalised after RC repair. An increase in glenohumeral elevation was consistently found. Furthermore, we demonstrated a decrease in lateral rotation and increase in posterior tilt were associated with increased humeral range of motion.

This study demonstrated improved humeral range of motion for abduction and forward flexion after an RC repair, as measured with 3D electromagnetic motion analysis. The observed increase in 3D range of motion is consistent with previous clinical results.[21, 22,

[29] Electromagnetic motion analysis has been applied to study shoulder motion in various other shoulder pathologic conditions, such as frozen shoulder, subacromial pain syndrome, and RC muscle tears.[9, 10, 12, 15, 25, 31] In these pathologies 3D analysis allows separate assessment of glenohumeral and scapulothoracic motion. Although contradictive results exist regarding treatment modalities for shoulder pathology, objective outcome variables such as this accurate 3D shoulder kinematical analysis are rarely used.[11, 31] For that matter, we analysed shoulder motion in RC tear patients before and after surgery and examined scapulothoracic rotations and glenohumeral elevation.

Kinematical analyses showed additional scapular lateral rotation during abduction in patients with an RC tear. This lateral rotation normalised after RC repair towards the scapular motion of the contralateral asymptomatic shoulder. In accordance to others, scapular lateral rotation has been reported to be increased in patients with an RC tear.[15, 25] Mell et al. reported increased scapulothoracic lateral rotation, and consequently, less glenohumeral motion in patients with an RC tear compared with controls with an intact RC.[15] In contrast, Paletta et al. did not observe a significant difference in scapulothoracic motion using plain radiographs, with planar radiographs potentially being less sensitive for kinematic changes.[2, 23] In comparison with patients with an RC tear, Paletta et al. reported more glenohumeral motion in healthy volunteers contributing to overall arm elevation, although this difference was not statistically significant.[23] on the basis of these findings, more glenohumeral elevation and less scapulothoracic rotation were expected after cuff repair. The observed increase in glenohumeral elevation after RC repair in our study is in agreement with the aforementioned studies and suggests that kinematics can be restored after RC repair.

The reasons for the observed scapulothoracic and glenohumeral kinematics in RC tears are not yet completely understood. Mell et al. suggested that more scapular lateral rotation facilitates an improved moment arm for deltoid tensioning.[15] The deltoid may compensate for lost RC function enabling the patient to maintain a functional range of motion.[4, 15] Likewise, a compensatory increase in lateral rotation has been postulated because the supraspinatus does not have a scapulothoracic moment arm to control movement of the scapula.[13] A comparable increase in lateral rotation was found in healthy volunteers after a suprascapular nerve block.[13] Furthermore, pain, changes in shoulder kinematics with age, compression of inflamed subacromial tissues, and instability at the glenoid, resulting in an unfavourable fulcrum for glenohumeral rotations, will have an impact on scapular motion. To study the effect of subacromial pain, scapular motion has been studied before and after the application of subacromial analgetics.[5, 25] Although we found normalization of 3D shoulder kinematics to the contralateral asymptomatic shoulder after RC repair, our results have to be interpreted with caution because contradictive results have been reported on the effect of subacromial anaesthetic infiltration on scapular lateral rotation.[5, 25] Less scapular lateral rotation after infiltration may suggest an effect of pain on lateral rotation.[25] Therefore, our findings do not prove that reinsertion of the RC causes more glenohumeral elevation.

However, our findings stress the importance of evaluating kinematics with validated 3D techniques.

This study has some limitations. Skin-bone displacements limit the possibility of an accurate measurement of scapular movements during overhand activities. This limits the scapulothoracic analysis of a complete abduction movement. The pair-wise analysis in this study is essential for the longitudinal analysis of scapular motion. Preoperatively some patients were unable to elevate the arm to full range of motion. Therefore, we had fewer observations at higher abduction intervals, with selected observations at higher abduction intervals. Although this had little impact on our conclusion that scapular rotations normalise after RC repair, we cannot determine in which abduction interval the 'normalization' after RC repair occurs. Although the contralateral shoulders were asymptomatic, these shoulders might have been affected by asymptomatic RC pathology.[33] Comparative research may outline whether the presented observations are the results of RC repair or regression to the mean. Comparisons between two unconstrained movements might differ in the plane of elevation or axial rotation. Nevertheless, we considered voluntary unguided movements essential for this analysis because standardization of movements would result in uncharacteristic, forced arm movement with a subsequent effect on kinematics. We included the slight variance within the plane of elevation and axial humeral rotation as a covariate in our model to correct for potential small differences. In addition, measurement error as a result of test-retest variability might influence results, even though the inter-session reliability (i.e. reproducibility) of the electromagnetic tracking device proved to be excellent.[24] Therefore, the estimated measurement error, based on reported reliability, was smaller than the observed differences.

In future studies, evaluations of shoulder pathology and therapeutic interventions for the shoulder should be performed with quantitative 3D kinematic analysis next to clinical and validated patient-reported outcome measures, thus having objective evaluation tools for analysis of the contradictive results of treatment modalities for the shoulder.

CONCLUSION

After RC repair, scapular motion during an abduction movement normalised towards a more symmetrical scapular motion pattern. In addition, more glenohumeral elevation was observed after RC repair. The observed changes in scapulothoracic motion were associated with an increase in range of motion. The normalization of shoulder kinematics suggests restored function of shoulder muscles with a subsequent effect on scapulothoracic and glenohumeral motion and increased overall arm elevation after RC repair.

ACKNOWLEDGEMENTS

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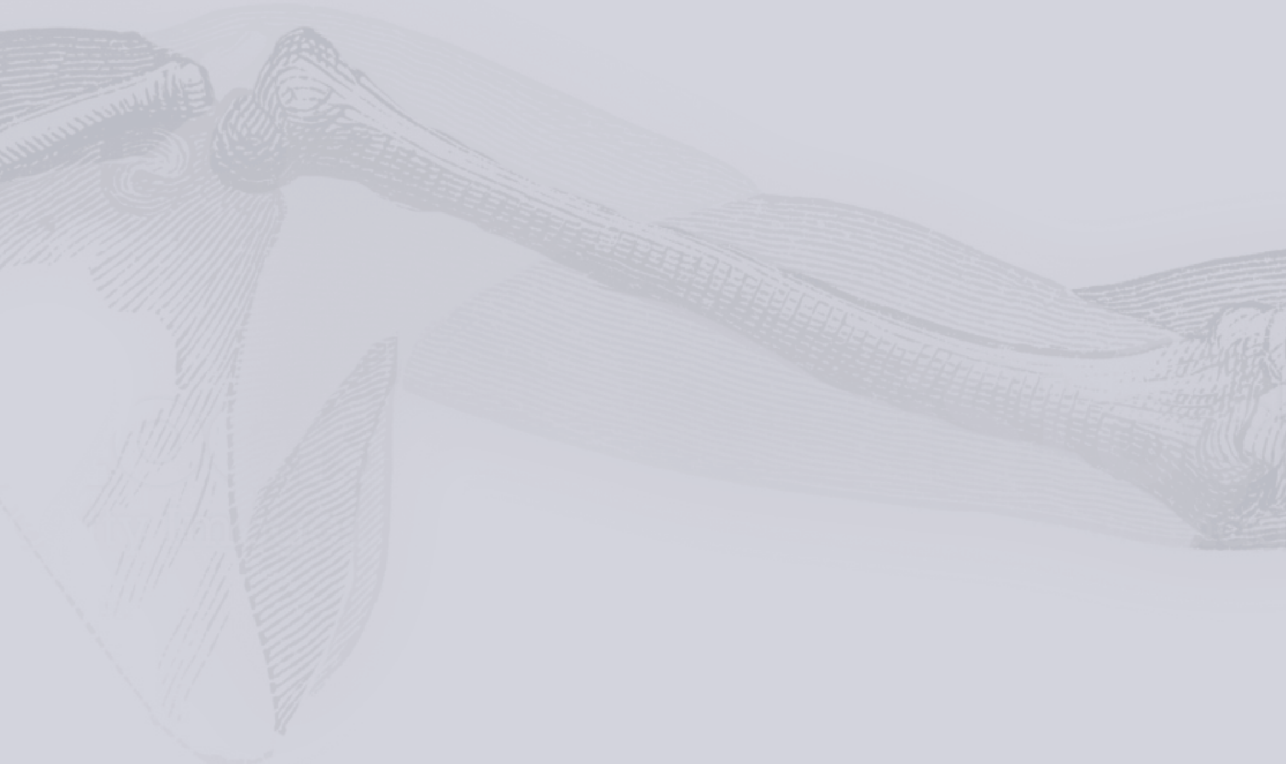

8

Teres major tendon transfer in the treatment of irreparable posterosuperior rotator cuff tears

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ABSTRACT

Background: Since long-term outcome of teres major tendon transfer surgery for irreparable posterosuperior rotator cuff (RC) tears is largely unknown, the primary aim of this study was to evaluate the long-term outcome of the teres major transfer. We also aimed to report on the results of a cohort of patients with a similar indication for surgery that underwent a latissimus dorsi tendon transfer.

Methods: In this prospective cohort study, we reported on the long-term results of 20 consecutive patients with a teres major for irreparable massive posterosuperior RC tears. Additionally, we reported on the results of the latissimus dorsi tendon transfer (n=19). Mean age was 60 (range 47 – 77) years. Outcomes included the Constant score (CS), pain at rest and during movement using Visual Analogue Scales (VAS).

Results: At a mean of ten years (range 8 – 12 years) following teres major transfer, the CS was still 23 points (95% confidence interval 14.6 – 30.9, $P < 0.001$) higher than preoperatively. VAS for pain at rest (21 mm; 95% confidence interval 4.0 – 38.9, $P = 0.016$) and movement (31mm; 95% confidence interval 16.0 – 45.1, $P < 0.001$) were lower than preoperative. We also found an increase in CS (32 points; 95% confidence interval 23.4 – 40.2, $P < 0.001$) and reduction of pain (26mm; 95% confidence interval 9.9 – 41.8, $P = 0.001$) six years after latissimus dorsi transfer.

Conclusions: Teres major tendon transfer is a treatment option to gain shoulder function and reduce pain in patients with an irreparable posterosuperior RC tear at a mean follow-up of ten years. The teres major tendon might be a valuable alternative to the commonly performed latissimus dorsi tendon transfer in the treatment of irreparable posterosuperior RC tears.

INTRODUCTION

The prevalence of rotator cuff (RC) tears in the general population increases substantially with age, from 0% to 3% in patients within their 30s to over half of the patients 70 years and older.[38] The majority of RC tears are asymptomatic and limited to the supraspinatus muscle, although the tear extends beyond the supraspinatus towards the infraspinatus muscle in 7% to 28%.[15, 16] Those massive posterosuperior RC tears often severely restrict activities of daily living due to pain, and limitation of shoulder mobility.[27]

Transfers of the latissimus dorsi or teres major tendon are viable treatment options to restore functional deficits and to reduce pain for the relatively young patient with a massive posterosuperior RC tear.[14, 18, 19] For posterosuperior massive RC tears, transfer of the latissimus dorsi transfer has been the most frequently reported procedure in literature with satisfactory long-term functional outcomes.[1, 11, 13, 14, 18, 21, 29, 31] As an alternative for transferring the latissimus dorsi, the teres major transfer has been advocated because of its potential favourable biomechanical orientation (i.e. better resembling the infraspinatus muscle).[4, 19, 26, 28] So far, only short-term postoperative results of the teres major tendon transfer have been reported with a maximal follow-up of three years.[3, 4, 19] Studies on long-term outcomes are warranted to provide information on the number of re-interventions (e.g. including conversions to reversed shoulder prosthesis after failed tendon transfer surgery and cuff tear arthropathy), to investigate durability of clinical improvements, and to examine whether the teres major can be used as a good alternative to the latissimus dorsi.

The purpose of this cohort study was to evaluate the long-term results of teres major tendon transfer surgery (mean 10 years, range 8 – 12 years) for patients with massive irreparable posterosuperior RC tears. Since shoulder surgery is primarily aimed at improving quality-of-life, this study will also provide a perspective on quality-of-life (i.e. SF-12 outcome measures) after tendon transfer surgery. Therefore, we also report on the results of a cohort of patients with a similar indication for surgery that underwent a latissimus dorsi tendon transfer at our institution with a mean follow-up of six years (range 5 – 8 years). We hypothesise that patients with an irreparable posterosuperior RC tear still have improved shoulder function and reduced pain 10 years after teres major tendon surgery.

MATERIALS AND METHODS

Participants

In this cohort study, we evaluated the outcomes of all consecutive patients who underwent teres major or latissimus dorsi tendon transfer for massive irreparable posterosuperior RC tears between April 2003 to April 2010 Leiden University Medical Centre, Leiden, the Netherlands. Initially from 2003 to 2007, the preferred muscle for tendon transfer surgery was the teres major. From 2007 to 2010, the latissimus dorsi tendon transfer was favoured because of its reported success in the literature.[13]

The diagnosis massive irreparable posterosuperior RC tear was established after assessing patient history, physical examination, radiographs and Magnetic Resonance Imaging with Arthrography (MRA). At baseline, all subjects subjectively reported invalidating pain and/or lost shoulder functionality that hampered daily life activities. A tendon transfer was only indicated if the patients exhibited an external rotation deficit in abduction during physical examination, without passive restriction. A massive irreparable posterosuperior RC was defined as: 1) type 3 RC tear according to Davidson et al. with involvement of the infraspinatus muscle; 2) stage II or III retraction according to Patte et al.; and 3) at least grade 2 fatty infiltration according to the modified classification reported by Fuchs et al..[8, 12, 32] Patients who suffered from a concurrent subscapularis muscle tear, axillary nerve injury, grade 3 or 4 glenohumeral osteoarthritis according to the Kelgren and Lawrence classification, symptomatic acromioclavicular osteoarthritis, and with restriction in passive shoulder mobility were not considered as eligible candidates for tendon transfer surgery[22]. Additionally, we excluded patients with a concomitant fracture, language barrier or in situ shoulder arthroplasty. The latter was considered an endpoint for this study. In total, 50 patients were eligible and received surgery between 2003 and 2010. Written informed consent was obtained from all participants.

Follow-up

Preoperative data and the evaluation approximately one year were obtained from a retrospective medical chart review. Short-term postoperative results of the teres major and latissimus dorsi transfer are previously reported.[18, 19, 34] For the purpose of the current study, patients were re-examined by an independent physician (AK/JFH). Of the 26 eligible subjects with a teres major tendon transfer, 20 patients (77%) attended the follow-up visit with a mean follow-up of ten years (range 8 – 12). Of the 24 eligible subjects with a latissimus dorsi tendon transfer, 19 patients (79%) attended the follow-up visit with a mean follow-up of six years (range 5 – 8). Loss to follow-up is reported in Figure 1. Baseline characteristics of the 39 included patients are described in Table 1 and complications that occurred in all 50 eligible subjects are described in Table 2.

Clinical assessment

The primary outcome of this study was to assess shoulder function, described with the Constant Score (CS).[6] Secondary outcomes were active range of motion, Visual Analogue Scale (VAS) for pain at rest, VAS for pain during movement of the arm and satisfaction with surgery. VAS for pain was reported by the patient on a 100mm bar, with 0mm indicating no pain, and 100mm indicating severe pain. Satisfaction was rated as either satisfied or unsatisfied with the outcome. Furthermore, we assessed health related general and disease-specific

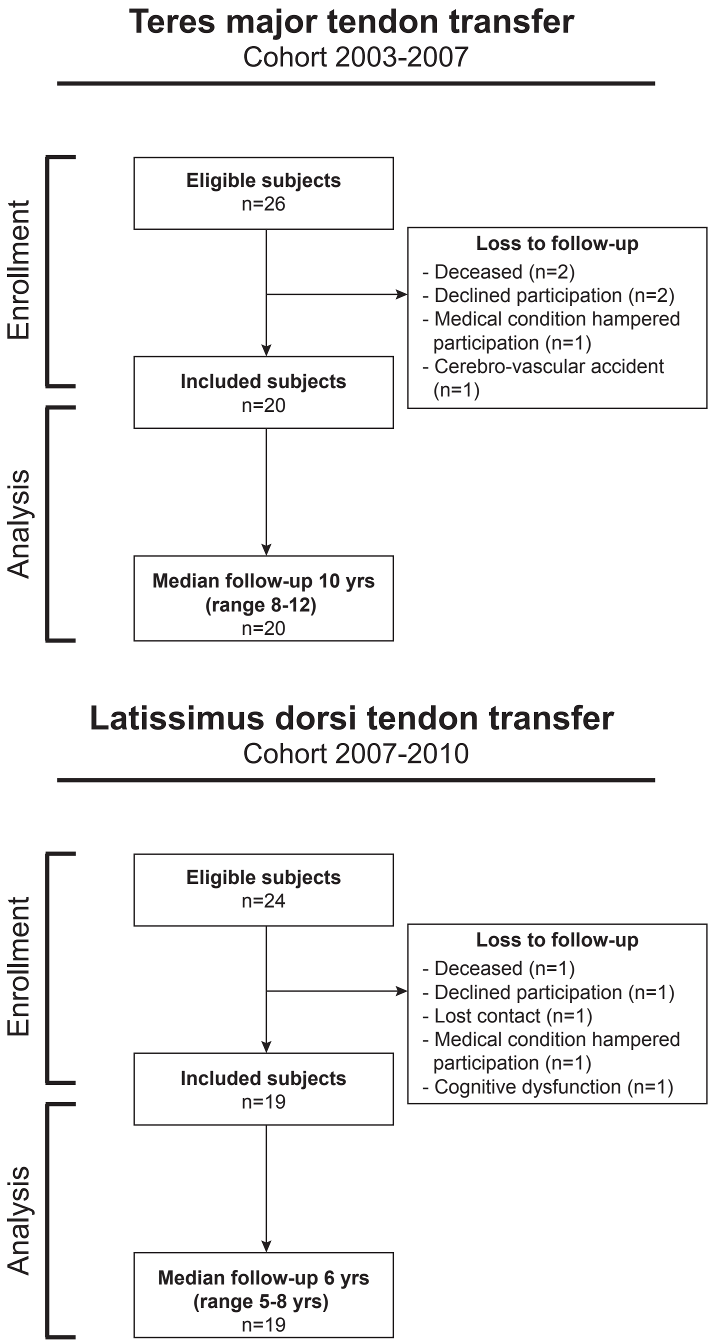


Figure 1. Flow-chart showing the number of included patients in the teres major tendon transfer cohort (left) and latissimus dorsi tendon transfer cohort (right).

quality-of-life at our final follow-up visit. The Short Form (SF)-12 was recorded to describe general health related quality-of-life after tendon transfer surgery.[36] The SF-12 expresses quality-of-life by means of a physical component summary (PCS) and mental component summary (MCS). To calculate the PCS and MCS, we used weights of indicator variables and constants that were obtained from a Dutch normative dataset and using the oblique rotation method.[30] Mean age- and sex-standardized scores (i.e. according to Dutch scores) were used to construct an age- and sex-corrected normative population.[30] This age- and sex-corrected normative population was created in order to investigate whether our patients did well when comparing patients with their counterparts in the general population. Disease-specific quality-of-life was recorded on the Western Ontario Rotator Cuff Index (WORC) with a score of 100% indicating an optimal shoulder-related quality-of-life.[23]

Table 1. Baseline characteristics of included subjects

	Teres major transfer Cohort 2003 to 2007 n= 20	***Latissimus dorsitransfer*** Cohort 2007 to 2010 n= 19
Age, yrs. †	60 (47 to 71)	59 (47 to 77)
Follow-up, mths. †	121 (94 to 144)	75 (58 to 92)
Male sex, n (%) ‡	9 (45%)	11 (58%)
Involved side (right) ‡	13 (65%)	16 (84%)
Dominant arm affected ‡	14 (70%)	14 (74%)
History of failed cuff repair ‡	7 (35%)	6 (32%)

Description of baseline characteristics of patients in both study cohorts. Data are described by the mean with range (†) and absolute numbers with a percentage (‡). Abbreviations: yrs, years; mths, months.

Table 2. Complications rate of the eligible patients

	Teres major transfer Cohort 2003 to 2007 n= 26	***Latissimus dorsitransfer*** Cohort 2007 to 2010 n= 24
Postoperative re-interventions, n (%)		
RSA for cuff tear arthropathy	1 (4%)	0
Hemi-arthoplasty for cuff tear arthropathy	0	1 (4%)
Subscapularis repair	2 (8%)	2 (8%)
Scar correction	1 (4%)	0 (0%)
Complications, n (%)		
Wound infection	1 (4%)	0
Hematoma	1 (4%)	0
Pulmonary embolism	1 (4%)	0
Atrial fibrillation	1 (4%)	0

Abbreviations: RSA, reversed shoulder arthroplasty.

Surgical technique

All tendon transfers were performed by one out of three orthopaedic surgeons (JN, RGGHN or PMR), using a two-incision surgical technique (Figure 2); surgical details have been described earlier.[18, 19] In short, patients were positioned in the lateral decubitus position with the arm in approximately 60 degrees of abduction and in internal rotation with the elbow 90 degrees flexed. First, a curved incision was made just proximal to the posterior axillar fold. Dissection was continued to expose the teres major and latissimus dorsi, and the anatomical insertion sites. The teres major was carefully separated from the latissimus dorsi. Either the teres major or latissimus dorsi was detached from the periosteum of the humeral shaft once the quadrangular space and radial nerve in the triangular interval were clearly identified. The tendon (i.e. either teres major or latissimus dorsi tendon) was marked by absorbable sutures and the muscle belly was released from the axillary fat. Subsequently, a second deltoid split incision was made to expose the proximal humerus. The tendon was tunnelled underneath the posterior part of the deltoid and over the long head of the triceps brachii muscle. The teres major or latissimus dorsi tendon was re-attached using RC anchors (DePuy Mitek Inc., Warsaw, Indiana, USA) with the arm in in slight abduction and full external rotation onto the lateral side of the major tubercle, caudal to the supraspinatus footprint, and ventral to the infraspinatus footprint. We did not attempt to close RC defects. No additional procedures (e.g. acromioplasty) were conducted.

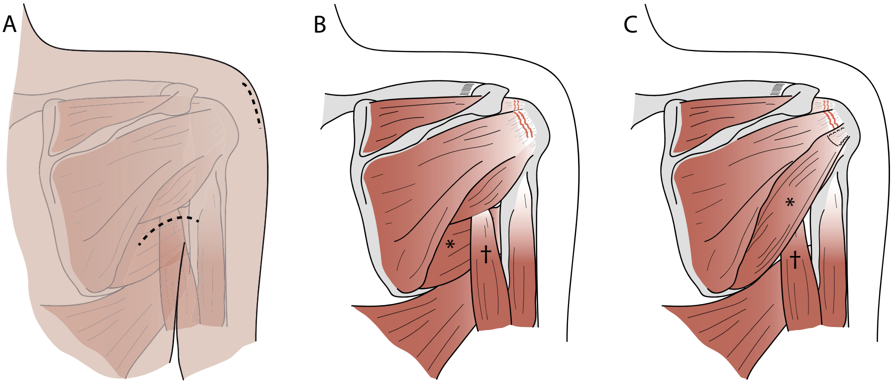


Figure 2. Surgical exposure and tendon insertion. A two-incision surgical technique was used: a curved incision was made just proximal to the posterior axillar fold and a deltoid split incision was made to expose the proximal humerus (Figure 2A). The preoperative anatomy is projected in Figure 2B. The deltoid muscle is removed from these illustrations. The teres major (*) runs underneath the long head of the triceps brachii muscle (†). In Figure 2C, the anatomy after transfer visualised. The teres major tendon (*) is tunneled underneath the posterior part of the deltoid and over the long head of the triceps brachii muscle (†). The teres major is inserted onto the lateral side of the major tubercle.

Following wound closure, the arm was immobilized in a shoulder brace with the arm in 0° of abduction and 0° of external rotation for six weeks. After six weeks, active movements were started under supervision of a physiotherapist. Strengthening exercises were allowed after three months.

Statistical analysis

Parametric data were described with means and range, nonparametric data were expressed with medians and interquartile range (IQR). Considering the repeated measurements and nonparametric distribution, generalized estimating equations were applied to assess changes in Constant Score (i.e. dependent variable) over time. Similar analyses were performed for VAS for pain. An autoregressive covariance structure of order one with heterogeneous variance was used to model correlated errors between consecutive assessment within a subject. The fixed factor was time (i.e. preoperative, at one years and at final follow-up). We expressed the change in outcome over time together with its 95% confidence interval (CI). These statistical analyses were performed using IBM SPSS statistics for Windows (version 20.0, IBM Corp, 2011, Armonk, New York, USA). A one-sample Student's t-test was performed to compare quality-of-life after a tendon transfer with quality-of-life of an age- and sex-corrected normalised population. These analyses were conducted using GraphPad Prism software for Windows (version 5.0, GraphPad software, La Jolla, California, USA). Significance level was set on a two-sided P value of 0.05.

RESULTS

Teres major tendon transfer

At a mean of 10 years (range 8 – 12 years) after teres major transfer, the median CS was 54 points, which was 23 points (95%CI 14.6 – 30.9, $P < 0.001$) higher than the preoperative score. The improvements in observed active forward elevation, abduction and external rotation in 90° of shoulder abduction were essentially preserved at ten years' follow-up (Table 3, Figure 3). We also observed a persistent reduction in pain. The CS at ten years' follow-up score was statistically significantly lower than at one year post-surgery (-8 points; 95%CI -14.5 – -0.4, $P = 0.037$), but no differences in VAS for pain at rest (5mm; 95%CI -5.3 – 15.5, $P = 0.337$) or during movement (10mm; 95%CI -7.5 – 28.0, $P = 0.259$) were observed. Of our 26 subjects eligible for participation, four (15%) patients were re-operated within ten years' follow-up (Table 2). Of 20 participants, 16 (80%) were satisfied with the results of the tendon transfer.

Table 3. Clinical outcomes after teres major tendon transfer

	Pre-operative	Follow-up at 1 yr.			
			Improvement (95% CI)		*P value*
Forward flexion†, °	70 (91)	100 (70)	19	(-4.1 – 41.9)	0.107
Abduction†, °	70 (91)	100 (100)	17	(0.7 – 32.9)	0.040*
External rotation in 90° abduction†, °	45 (60)	60 (28)	21	(3.5 – 39.4)	0.019*
Constant Score†, points	35 (25)	68 (19)	30	(21.9 – 38.5)	<0.001*
VAS pain at rest†, mm	45 (69)	5 (23)	-27	(-41.0 – -12.1)	<0.001*
VAS pain on movement†, mm	49 (43)	0 (21)	-41	(-52.5 – -29.0)	<0.001*
		Follow-up at 10 yrs.			
			Improvement (95% CI)		*P value*
Forward flexion†, °		125 (54)	28	(3.8 – 52.2)	0.023*
Abduction†, °		123 (78)	26	(6.2 – 46.3)	0.010*
External rotation in 90° abduction†, °		43 (39)	6	(-8.3 – 20.9)	0.400
Constant Score†, points		54 (29)	23	(14.6 – 30.9)	<0.001*
VAS pain at rest†, mm		4 (23)	-21	(-38.9 – -4.0)	0.016*
VAS pain on movement†, mm		14 (43)	-31	(-45.1 – -16.0)	<0.001*

Shoulder function and pain scores at baseline, at a mean follow-up of one year and at final follow-up assessed with generalized estimating equations. Abbreviations: CI, confidence interval; VAS, visual analogue scale; yrs; years, mm, millimetre.

* Statistically significant difference at P <0.05.

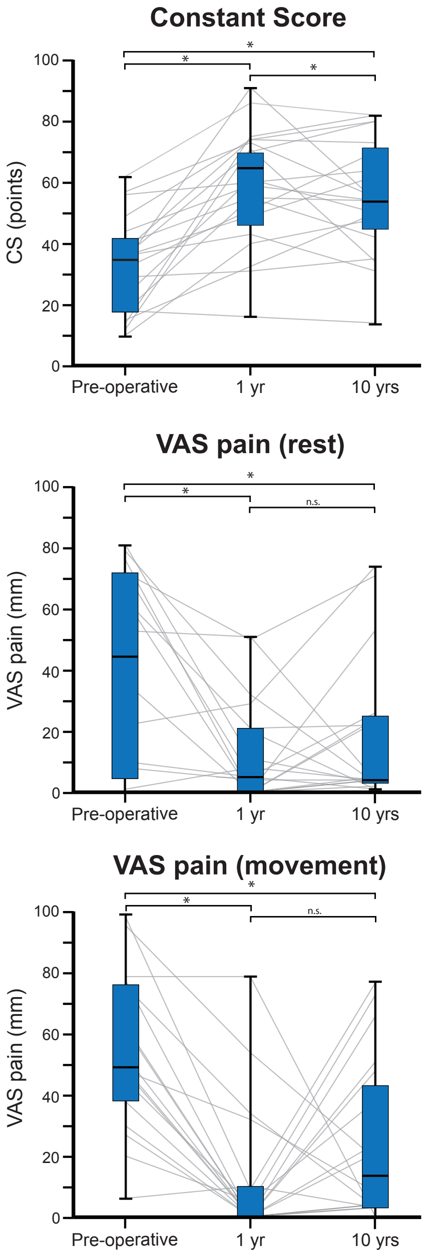
† Median and interquartile range (IQR).

Latissimus dorsi tendon transfer

The median CS at a mean of six years (range 5 – 8 years) after latissimus dorsi transfer was 75 points and was 32 points (95%CI 23.4 – 40.2, P < 0.001) higher than the preoperative score. The improvements in observed active forward elevation, abduction and external rotation during in 90° of shoulder abduction were preserved at six years' follow-up (Table 4, Figure 4). We also observed a lasting reduction in pain at rest and during movement of the arm. The final follow-up score was not statistically significantly different from the outcome at one year for the CS (1 point; 95%CI -6.3 – 7.4, P = 0.880), VAS for pain at rest (6mm; 95%CI -1.7 – 13.8, P = 0.125), but VAS during movement was significantly increased (15mm; 95%CI 0 – 30.4, P = 0.050). Of our 24 subjects eligible for participation, three (13%) patient received additional surgery within six years' follow-up (Table 2). The majority of the patients (89%, 17 out of 19 participants) was satisfied with their outcomes.

Quality-of-life after a tendon transfer

The mean PSC and MSC after teres major tendon transfer were 41.1 points and 46.9 points, respectively (Figure 5). The PCS and MSC were lower in the surgical group than in the age- and sex-corrected normative population with 6 points (95%CI -11.31 – -1.12, P = 0.019) and 2 points (95%CI -7.73 – 2.92, P = 0.356), respectively. The median postoperative WORC score at ten years was 54% (IQR 35).


Constant Score

VAS pain (rest)

VAS pain (movement)

Figure 3. Results of the teres major tendon transfer. Plots show the course of shoulder pain and function after a teres major tendon transfer from preoperative, at a mean follow-up of two years and at a mean follow-up of ten years in individual patients (grey lines). Boxplots indicate the median, interquartile range and range of outcome measures.

[*] Statistically significant difference at $P < 0.05$.

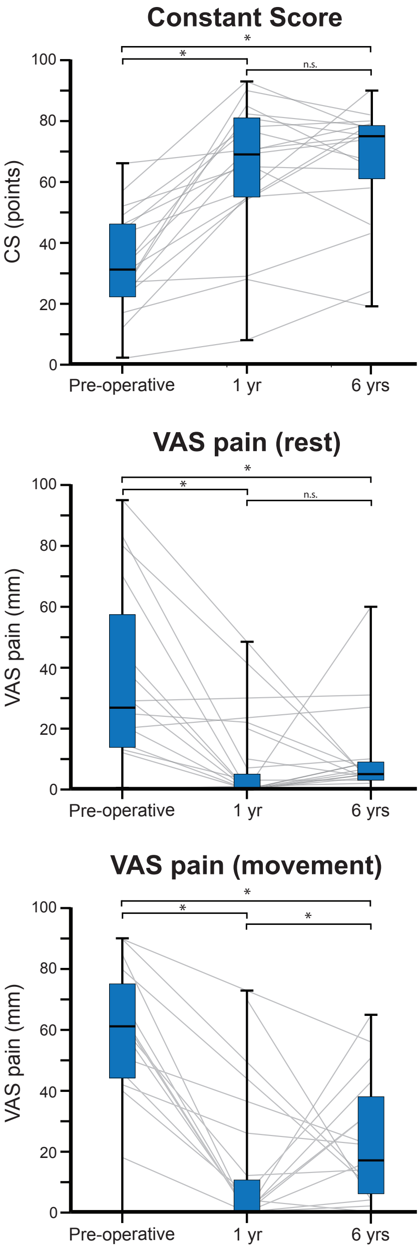


Figure 4. Results of the latissimus dorsi tendon transfer. Plots show the course of shoulder pain and function after a latissimus dorsi tendon transfer from preoperative, at a mean follow-up of two years and at a mean follow-up of six years in individual patients (grey lines). Boxplots indicate the median, interquartile range and range of outcome measures.

[*] Statistically significant difference at $P < 0.05$.

Table 4. Clinical outcomes after latissimus dorsi tendon transfer

	Pre-operative	Follow-up at 1 yr.			
			Improvement (95% CI)		*P value*
Forward flexion[†], °	90 (70)	130 (60)	37	(15.8 – 57.3)	0.001[*]
Abduction[†], °	80 (60)	120 (60)	43	(30.2 – 70.8)	<0.001[*]
External rotation in 90° abduction[†], °	20 (48)	65 (20)	42	(26.0 – 58.9)	0.008[*]
Constant Score[†], points	31 (25)	69 (27)	31	(22.4 – 40.1)	<0.001[*]
VAS pain at rest[†], mm	27 (50)	0 (7)	-32	(-46.4 – -17.5)	<0.001[*]
VAS pain on movement[†], mm	61 (38)	0 (9)	-49	(-65.3 – -32.1)	<0.001[*]
		Follow-up at 6 yrs.			
			Improvement (95% CI)		*P value*
Forward flexion[†], °		150 (35)	42	(21.8 – 61.8)	<0.001[*]
Abduction[†], °		160 (75)	51	(30.2 – 70.8)	<0.001[*]
External rotation in 90° abduction[†], °		70 (65)	28	(7.6 – 49.2)	0.008[*]
Constant Score[†], points		75 (21)	32	(23.4 – 40.2)	<0.001[*]
VAS pain at rest[†], mm		5 (6)	-26	(-41.8 – -9.9)	0.001[*]
VAS pain on movement[†], mm		17 (39)	-33	(-48.5 – -18.4)	<0.001[*]

Shoulder function and pain scores at baseline, at a mean follow-up of one year and at final follow-up assessed with generalized estimating equations. Abbreviations: CI, confidence interval; VAS, visual analogue scale; yrs; years, mm, millimetre.

[*] Statistically significant difference at $P < 0.05$.

[†] Median and interquartile range (IQR).

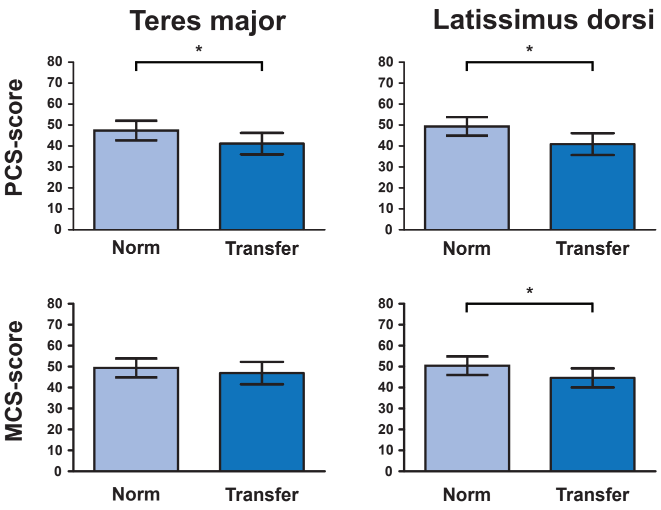


Figure 5. General quality-of-life after a tendon transfer. Comparison of mean (with 95% Confidence interval) general quality-of-life between the tendon transfer group and age- and sex-corrected normative population. Abbreviations: PCS, physical component summary; MCS, mental component summary; Norm, age- and sex-corrected normative population.

[*] Statistically significant difference at $P < 0.05$.

After a latissimus dorsi transfer, mean PSC and MSC were 40.9 and 44.6 points, respectively. The difference in score was 8 points (95%CI -13.62 – -3.21, P = 0.003) and 6 points (95%CI -10.38 – -1.23, P = 0.016) lower after surgery for the PCS and MSC score, respectively. The median WORC after a latissimus dorsi tendon transfer was 61% (IQR 42).

DISCUSSION

Postoperative gain in shoulder function and relieve of pain after teres major tendon transfer at ten years were persistent through follow-up. We also showed an increase in shoulder function and reduction in pain at mid-term follow-up after latissimus dorsi tendon transfer. Quality-of-life was slightly decreased in patients who underwent tendon transfer surgery for massive irreparable posterosuperior RC tears when compared to a normalised control group.

Our results of the teres major tendon transfer at ten years' follow-up are comparable to the long-term follow-up reported outcomes of the latissimus dorsi transfer in literature. Both Gerber et al. (CS from 47 to 64 points) and El-Azab et al. (CS 36 from to 62 points) described an improvement in shoulder function with a follow-up of more than 9 years after latissimus dorsi transfer.[11, 13] Likewise, our satisfaction rate of 80% and 4% conversion rate to a (reversed) shoulder arthroplasty after a teres major tendon transfer were comparable to these prior reports concerning latissimus dorsi tendon transfer.[11, 13] While several other groups have reported on the postoperative outcomes of the latissimus dorsi tendon transfer[1, 11, 13, 14, 18, 21, 29, 31], just Celli et al. described their mid-term experience with teres major tendon transfer in the treatment of an irreparable massive rotator cuff tear.[3, 4] Celli et al. showed a postoperative functional gain on the mean CS of 22 point at 14 months, and 35 points at 3 years.[3, 4] These mid-term results are comparable to our findings at 2 years.[19] In this study, we are the first to show that the improvement in shoulder function and pain after a teres major tendon transfer is maintained over the course of ten years, and these data are equivalent to long-term results of the latissimus dorsi tendon transfer.

Teres major tendon transfer was initially described by L'Episcopo in obstetrical plexus injuries.[25] In the treatment of massive irreparable posterosuperior RC tears, Gerber et al. introduced the latissimus dorsi tendon transfer.[14] The teres major transfer could be favourable as substitute for the infraspinatus muscle due to its scapulohumeral orientation.[3, 4] A teres major transfer will result in a more functional augmentation in biomechanical alignment with the action of the infraspinatus. This idea was further propagated by model simulations that identified the teres major tendon transfer as the optimal procedure to restore external rotation leading to improved activities of daily living.[26] Following a teres major tendon transfer, large functional improvements were observed like washing the contralateral axilla and reaching. The transfer of the latissimus dorsi resulted in a lower number of successful functional movement simulations (e.g. perineal care).[26] Theoretically, it may become more difficult to push on the arms of a chair to stand up after latissimus dorsi transfer. During surgical exposure, the teres major tendon is easily identified because it overlies the latissimus dorsi. Nevertheless, the length of the teres major tendon is limited, making it technically more demanding if the tendon is not cut flush from the bone.[2] The teres major has a reliable vascular supply, and has sufficient structural properties with respect to tension and excursion to reach the lateral site of the supraspinatus footprint at the greater tuberosity.[2, 19, 20, 35] When attaching the tendon at this location, the transferred muscle has a biomechanically good position that allows the delivery of external rotation and elevation during arm abduction.[26, 28]

The effectiveness of transfer surgery is frequently assigned to an active contribution of the transferred muscle in shoulder movement, ideally with synergistic muscle activity during abduction and external rotation.[1, 9, 14, 18, 21, 34] Its effectiveness may also rely on reinstating humeral head position via increased caudally directed forces counteracting increased deltoid forces, and a potential tenodesis effect. Interestingly, inferior functional results were reported in the presence of insufficient torques produced by the subscapularis or teres minor muscle.[1, 7, 14] Both muscles are assumed to have an important stabilizing function in the absence of forces generated by the infraspinatus.[37] In a cadaveric model that simulated the distribution of forces within the glenohumeral joint after a latissimus dorsi tendon transfer, activation of the subscapularis muscle has been found to counteract anterior translation of the humerus.[37] This finding suggests that a torn subscapularis muscle might be considered as a contraindication for tendon transfer.[37] Similarly, deficiency of the teres minor has been associated with inferior postoperative shoulder function because its activity may contribute to external rotation.[31]

In recent years the indication for reversed total shoulder arthroplasty has expanded and has become a therapeutic option for patients with a massive RC tear even in the absence of glenohumeral osteoarthritis.[10] Revision rates of reversed total shoulder arthroplasty up to 38% at ten years' follow-up are a considerable cause for concerns, especially in a relatively young patient.[10] Postoperative external rotation deficits may further increase the need for additional tendon transfers to recover activities of daily living.[33] A tendon transfer should be considered as an alternative to reversed total shoulder arthroplasty in posterosuperior RC tears, especially since a reversed total shoulder arthroplasty remains an option if function deteriorate over time.

There are several limitations concerning this study. Firstly, baseline Constant scores were obtained via a retrospective chart-review and follow-up evaluations were performed by a different examiner. The observed improvement in all outcomes are substantial and assumed to be beyond measurement error that might have been introduced by inter-observer variability (+/-18 points) and the change that is considered clinically relevant.[5, 6, 17, 24] Secondly, not all eligible subjects were available for this follow-up study, which can be considered a weakness. However, loss of follow-up was frequently related to death, cerebrovascular event or dementia, and thus we assume that loss of follow-up has not severely skewed our conclusions. Finally, we did not evaluate the progression of radiologic features in our subjects.

Future research may further elucidate the value and patient specific indication for tendon transfer surgery in patients with a massive posterosuperior RC tear. This study provided data regarding the number of re-interventions and long-term functional improvement after teres major tendon transfer. Since both tendons, the teres major and the latissimus dorsi, yield potential advantages, a randomised controlled trial is needed to compare the effectiveness of both tendon transfers. This trial is underway (Dutch Trial Register no. 4721).

CONCLUSION

Our long-term data indicate that the teres major transfer restores shoulder function and reduces pain in patients with a massive irreparable posterosuperior RC tear. We are the first to show that improvement in shoulder function after teres major tendon transfer lasts for over ten years. General health related quality-of-life after tendon transfer surgery was lower than in a normalised population. Since results at ten years' follow-up are comparable to the outcomes after a latissimus dorsi as reported in literature, the teres major might be an alternative to latissimus dorsi tendon transfer. For that matter, we consider both tendon transfers as a functional and long-term surgical option in the treatment of massive posterosuperior RC tears.

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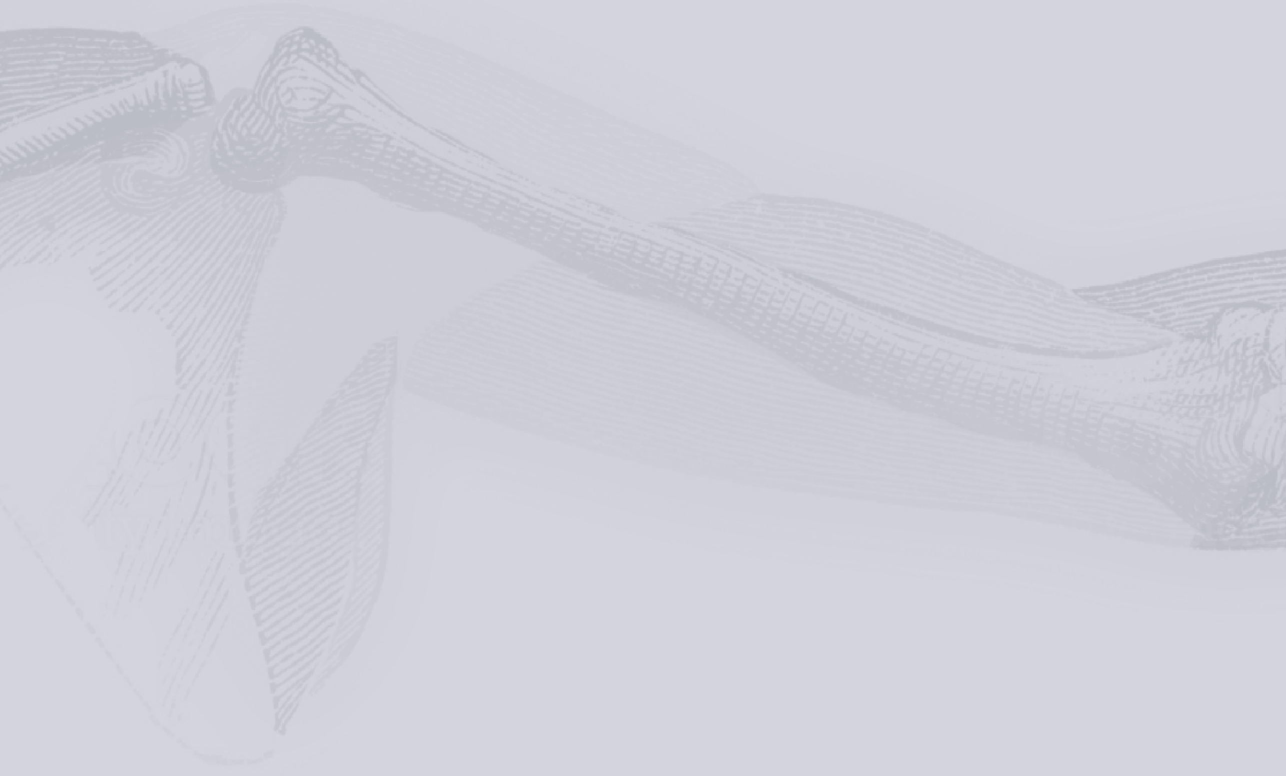

9

Summary and general discussion

At the start of the SISTIM research project, the pathophysiology of the subacromial pain syndrome (SAPS) was poorly understood and literature lacked high-quality evidence justifying surgical treatment. The goals of this thesis were to evaluate the long-term outcomes of arthroscopic subacromial decompression as the common surgical intervention for SAPS; to create a biomechanical rationale for successful treatment options by studying patterns in shoulder muscle activity and kinematics in patients with SAPS; and to evaluate the association between the size of structural rotator cuff (RC) defects and shoulder kinematics. For that matter kinematics and shoulder biomechanics in symptomatic shoulders are analysed.

ARTHROSCOPIC DECOMPRESSION UNDER SCRUTINY

Up to recently, attrition of the RC under a hooked acromion or the coracoacromial ligament was assumed to cause subacromial impingement. As a result, arthroscopic subacromial decompression (i.e. acromioplasty) was widely used as a standard treatment for subacromial pain in the orthopaedic clinical practice, although high-quality evidence supporting its efficacy was limited.[32, 51, 68] Earlier work had shown no differences in shoulder pain and function between arthroscopic bursectomy alone or a bursectomy in combination with acromioplasty 2.5 years after treatment.[25] Although no short-term differences were found, the treatment effect of acromioplasty on clinical outcomes after 10 or 20 years were not studied although it has been hypothesised that repeated fraying of the RC under the hooked acromion may cause shoulder pain. In **Chapter 2** we evaluated the long-term effect of arthroscopic subacromial decompression in patients with SAPS in a randomised controlled clinical trial. The results showed no treatment effect of subacromial decompression in improving shoulder pain (Visual Analogue Scale; 95% confidence interval [CI] -21 - 9, P = 0.43) and function (Constant Score; 95%CI -5 - 16, P = 0.32) at a median of 12 years' follow-up. Moreover, acromioplasty seems not to protect the RC from tearing, since both groups with bursectomy alone and in combination with acromioplasty had comparable numbers (i.e. 10% versus 17%) of RC tears. These findings showed no treatment effect of acromioplasty and supported the advice against arthroscopic subacromial decompression in the treatment of chronic SAPS.

The justification of acromioplasty mainly relied on the positive results shown in cohort and non-comparative studies.[2, 3, 16, 56] Randomised studies suggesting no treatment effect received much more criticism.[25, 29, 36] Some orthopaedic surgeons from the shoulder community pointed at potential methodologic flaws of randomised work, trusting more on the evidence of the widely performed acromioplasty provided by non-randomised studies.[22, 29] In 2018, two additional randomised controlled clinical trials were published in well-respected scientific journals supported our results presented in this thesis.[1, 50] These studies did not show a beneficial clinically relevant effect of arthroscopic subacromial decompression compared to sham surgery on pain and shoulder function.[1, 50] When subacromial decompression was compared to physiotherapy alone, pain and shoulder function were significantly better after arthroscopic acromioplasty. However, these differences did not exceed the minimal clinically important difference, and could relate to surgical placebo effects.[50] Together with the available randomised clinical trials such as the study presented in this thesis, these two trials from 2018 contributed to the growing evidence against the favourable effect of subacromial decompression.[1, 7, 36, 50] Because of the absence of convincing evidence, the Dutch Orthopaedic Society recommends to use a conservative treatment protocol for SAPS. The current advice is to consider acromioplasty only after failure of extensive conservative treatment and this advice will probably be sharper formulated in their revised recommendations.[14, 48] Other national societies and international guidelines also changed their recommendation with respect to SAPS and now recommend not to perform acromioplasty or preserve acromioplasty for more selected patients with persisting symptoms after extensive conservative treatment.[22, 33, 66]

BIOMECHANICS AND KINEMATICS IN SUBACROMIAL PAIN SYNDROME

The lack of a uniform definition regarding patient characteristics and absence of accurate clinical tests to confirm the diagnosis for this pain syndrome may have contributed to heterogeneity in study populations.[11, 52] As a result, inconsistent study outcomes are reported in literature. In the SISTIM project, shoulder biomechanics and kinematics have been studied in a more homogenous sample created by including patients diagnosed with SAPS with comparable findings on magnetic resonance imaging (MRI) reflecting a more homogenous anatomic substrate for pain.[12]

Shoulder biomechanics and kinematics of patients with SAPS are compared to asymptomatic volunteers in **Chapter 3**. We found a lower activation ratio for the pectoralis major (i.e. relatively less agonistic activity) and higher activation ratio for the teres major (i.e. relatively less antagonistic activity) in the subacromial pain group. There was no difference in the activity of scapular stabilizers between patients with subacromial pain and asymptomatic controls. The contribution of glenohumeral motion to overall elevation (at 120° abduction mean difference -9°; 95% CI -14 - -3, P = 0.003) and external rotation (at 120° abduction mean difference -8°; 95% CI -13 - -3, P < 0.001) was lower in patients with SAPS indicating more scapulothoracic motion. Less external rotation has been demonstrated to bring the greater tuberosity in closer contact with the coracoacromial arch, shift contact pressures to the posterolateral RC and to bring the humeral head (especially between 60° to 120° of arm elevation) in closer contact with the acromion [19, 46]. The latter may contribute to the subacromial inflammation seen in patients with SAPS. Moreover, the teres major has been suggested to counteract cranially directed destabilizing glenohumeral forces.[10, 61] We found a higher activation ratio for the teres major (i.e. relatively less antagonistic activity) during arm elevation in patients with subacromial pain, suggesting impaired function of the teres major as a humeral head depressor. This biomechanical knowledge is essential to unravel the pathophysiology of subacromial pain, to identify subgroups of patients with subacromial pain and to explain how treatments work. Physiotherapy directed at the teres major may enhance the antagonistic activity of the teres major to improve its function as humeral head depressor.

Orthopaedic surgeons and physiotherapists link scapular dyskinesis to the presence of SAPS.[11, 39, 42, 65] Scapular dyskinesis is clinically identified as an asymmetry in scapulothoracic motion between both shoulders.[65] Because scapular dyskinesis is believed a pathological finding, some rehabilitation programmes focussed on scapulothoracic kinematics in SAPS.[42] Quantitative motion analysis revealed scapular dyskinesis in SAPS, but inconsistent outcomes have been reported potentially due to heterogeneity in selecting criteria among studies.[17, 18, 39] In **Chapter 4**, we investigated the presence of asymmetry in scapulothoracic motion in a group of patients with subacromial pain after radiologic shoulder examination creating a group with a more comparable anatomic substrate for pain than in existing literature. We found more scapular internal rotation (mean difference 5° at 120° abduction; 95%CI 0 - 10, P = 0.034) in the affected shoulder, but did not find a difference in scapulothoracic lateral rotation (95%CI -3 - 4, P = 0.964) or posterior tilt (95%CI -6 - 3, P = 0.413) between the affected and unaffected shoulder. Interestingly, the absence of asymmetric scapulothoracic lateral rotation suggest that both shoulders are exposed to comparable biomechanics, since we demonstrated a difference between patients and asymmetric controls in chapter 3. Asymmetry of scapulothoracic motion may either cause pain by dynamically reducing subacromial space, be the consequence of pain or does not play a role and could be a normal observation in patients with shoulder pain. To improve our knowledge of pain and its effect on shoulder kinematics, we examined the effect of subacromial anaesthetics on scapulothoracic motion expecting more symmetrical kinematics after infiltration of subacromial anaesthetics. In other words, we expected pain to cause deviations in scapulothoracic motion. In contrast to our hypothesis, there was more asymmetric shoulder motion with more scapulothoracic internal rotation and less posterior tilt after infiltration than before. Subacromial infiltration with lidocaine was not an effective way to restore symmetrical shoulder motion. More internal rotation and less posterior tilt are known to reduce subacromial volume and thus are less favourable in SAPS.[38, 60] In other words, our kinematic data indirectly show that the removal of pain by infiltration of subacromial anaesthetics caused a reduction of subacromial volume. A possible explanation for our findings is that pain controls a local protecting mechanism which reduces the contact of inflamed tissues and the acromion. Moreover, this may identify asymmetric scapulothoracic kinematics in the pathophysiologic pathway for developing shoulder pain. Finally, we found an association between less scapular lateral rotation (i.e. upward rotation) and higher patient-reported pain scores. More contact between inflamed subacromial tissues with the acromion may explain the higher self-reported pain scores in our study, because less lateral rotation brings the RC in closer proximity to the acromion.[38]

BIOMECHANICAL AND KINEMATIC CHANGES IN THE SHOULDER FOLLOWING A ROTATOR CUFF TEAR

Shoulder biomechanics in the presence of an RC tear have been further clarified by comparing shoulder biomechanics on specimens with an intact RC to biomechanics after an artificial RC tear was created.[23, 64] It was shown that the supraspinatus significantly contributes to the elevating torque during glenohumeral elevation as it has also been previously observed by Inman in 1944.[23, 31, 64] The absence of supraspinatus torques lead to a significant increase in deltoid muscle force and forces delivered by the intact portion of the RC.[23, 43, 62, 64] The m. subscapularis and posterior RC has also been shown to compensate for lost torques in the presence of a supraspinatus tear to facilitate a stable fulcrum for shoulder movement.[23] If stabilizing forces from the posterior cuff decrease, the humerus will cranially translate relative to the scapula and the ability for shoulder movement will be lost.[4, 59, 64] This biomechanical principle emphasizes the essential function of the posterior RC (i.e. teres minor and infraspinatus) and anterior RC (i.e. subscapularis) to maintain glenohumeral stability. It is also known as the "transverse force couple" (although this couple does not fully meet the definition in physics.[4, 23, 53, 64] The requirements for the delivery of a sufficient amount of torque in the presence of an RC tear have been calculated in computer models.[41, 62] In line with the findings from cadaveric studies, Steenbrink et al. confirmed with computer modelling the significant contribution of infraspinatus and teres minor forces for maintaining the stable fulcrum for shoulder motion.[62]

These biomechanics were considered to have an important impact on shoulder kinematics in patients, but this had to be validated. Existing work studied the effect of three-dimensional kinematics in patients with an RC tear, but did not account for the effect of tear size on shoulder kinematics.[45, 49, 58] In a cross-sectional study, we demonstrated the association of RC tear size and shoulder kinematics using three-dimensional electromagnetic motion analysis in **Chapter 5**. Patients with a massive RC tear involving the supraspinatus and infraspinatus had reduced glenohumeral elevation compared to patients with an isolated supraspinatus RC tear (mean difference 10° at 110° abduction; 95% CI 4 – 17, P = 0.002) or with an intact RC (mean difference 16° at 110° abduction; 95% CI 11 – 21, P < 0.001) during abduction, and forward flexion. This decrease in glenohumeral elevation coincided with an increase in scapulothoracic lateral rotation. We did not demonstrate a significant difference in glenohumeral motion between the patients with SAPS and an isolated supraspinatus tear. These observations may reflect the biomechanical shift of forces in the shoulder with a massive RC tear. The kinematics are in line with the assumed essential contribution of the infraspinatus to preserve glenohumeral elevation in the presence of a supraspinatus tear. Because shoulder kinematics are associated with RC tear size, quantitative evaluation of shoulder kinematics can potentially be used in a diagnostic process of the patients with shoulder pain.

While designing a study that should examine molecular and cellular signatures of rotator cuff degeneration, it was postulated that structural defects in the shoulder may have an effect on the cell biology of other intact shoulder muscles, because adaptations in joint biomechanics change the entire shoulder system. In **Chapter 6**, we tested the beforementioned biomechanical concept of changed compensatory mechanical load of shoulder muscles in patients with a (postero)superior RC tear and its association with the development of muscle atrophy on patients. Prior animal and cross-sectional studies demonstrated less atrophy in the presence of an RC tear.[30, 35, 44] In an observational study with a mean of 3-years follow-up, we showed that the surface area of teres minor and deltoid muscles in patients with an intact RC on Magnetic Resonance Imaging decreased with age, which indicated muscle atrophy of these two intact muscles. In patients with a (postero)superior RC tear, however, the teres minor atrophied more slowly or even grew. This finding was most apparent in patients under the age of 50 years. Our findings are in line with our biomechanical rational and suggested that muscle atrophy in the shoulder can be reduced when an increase in mechanical load is exerted onto the muscle. A compensatory increase in teres minor muscle volume may compensate for lost infraspinatus forces, especially in younger patients, resulting in a stable fulcrum for joint motion. The latter could be an explanation for the remarkable discrepancy between the extend of an RC tear and shoulder complaints, in which a young patient with an extensive RC tear have no pain and excellent shoulder mobility.

KINEMATICAL AND CLINICAL OUTCOMES OF SURGERY

Disturbed scapula-humeral movement has been considered a *"sine qua non"* for the diagnoses of an RC tear. In chapter 5, we showed a decrease in glenohumeral elevation and increase in scapulothoracic lateral rotation in patients with a (massive) RC tear. Although ample studies investigated the effect of RC repair on pain and elevation angles using semi-quantitative methods, shoulder motion before and after RC repair had not been appraised with quantitative three-dimensional electromagnetic motion analysis. In **Chapter 7**, we evaluated three-dimensional shoulder motion in patients before and one year after RC repair. We demonstrated an increase in glenohumeral elevation and less scapulathoracic lateral rotation following an RC repair. Overall range of thoracohumeral motion increased after surgery. Postoperative shoulder kinematics were more comparable with the kinematics of the asymptomatic contralateral shoulder. These observed changes in shoulder kinematics following RC repair coincides with improved shoulder range of motion and more symmetrical shoulder movement after surgery. Whether these changes in shoulder kinematics are the result of the relieve of shoulder related pain or restored functionality of the reinserted RC muscle on the humeral head, remains unclear. Nevertheless, the evaluation of three-dimensional shoulder motion provides a quantitative measurement of shoulder movement, which might be a valuable alternative to semi-quantitative methods.

Fatty infiltration or retraction hampers a rotator cuff repair in patient with a massive posterosuperior RC tear. In these patients, a tendon transfer of the teres major or latissimus dorsi to the infraspinatus footprint may serve as a salvage procedure for the relatively young patient with a massive posterosuperior RC tear.[5, 6, 20, 26] Although the glenohumeral teres major has been suggested biomechanically superior to the humerothoracic latissimus dorsi, the latissimus dorsi tendon transfer got popularized by Gerber et al. and is nowadays the most commonly described tendon transfer.[20, 40] Only short-term outcomes have been reported for the teres major tendon transfer.[5, 6, 26] In **Chapter 8**, we described the long-term (mean 10 years) outcomes of the teres major tendon transfer in a cohort of patients with a massive irreparable posterosuperior RC tear. Shoulder function was still higher ten years after teres major transfer than preoperative. Similarly, lower pain scores were observed ten years after surgery. Our long-term data demonstrated that improvement in shoulder function and relieve of pain after teres major tendon transfer lasts for over ten years. A secondary aim of this study was to provide data on shoulder function and pain after latissimus dorsi tendon transfer surgery in cohort of patients with a similar indication for surgery with a mean follow-up of six years. Six years after latissimus dorsi transfer shoulder function and pain scores were improved compared to the preoperative scores. Moreover, this study described the general health related quality-of-life after tendon transfer surgery. Health related quality-of-life was significantly lower than in a normalised population indicating the severe impact of an RC tear. This study proved that teres major tendon transfer may generate successful outcomes even after ten years' follow-up. For that matter, the teres major tendon might be a valuable alternative to the commonly performed latissimus dorsi tendon transfer in the treatment of irreparable posterosuperior RC tears.

MAIN CONCLUSIONS

- Arthroscopic subacromial decompression/acromioplasty is not effective in improving shoulder function and relieving pain in patients with SAPS (Chapter 2).
- Patients with subacromial pain can still develop an RC tear after an acromioplasty (Chapter 2).

- Patients with SAPS have less glenohumeral elevation (with more scapulothoracic lateral rotation) and less glenohumeral external rotation (with more scapulothoracic posterior tilt) when elevating the arm (Chapter 3).
- Patients with SAPS have less teres major antagonistic activity during abduction moments than asymptomatic controls resulting in a lower activation ratio (Chapter 3).
- Subacromial infiltration with an anaesthetic does not restore symmetrical shoulder kinematics in patients with SAPS (Chapter 4).
- Less lateral rotation (i.e. upward rotation) and less posterior tilt of the scapula are associated with higher patient-reported pain in SAPS (Chapter 4).
- In-vivo shoulder kinematics are associated with RC tear size. Large tears involving both the supraspinatus and infraspinatus coincides with less glenohumeral elevation and more scapulothoracic lateral rotation during arm elevation (Chapter 5).
- While the cross-sectional surface area of the teres minor and deltoid muscle gradually decrease with age, these muscles show a limited decline or even an increase in cross-sectional surface area in patients with a (postero)superior RC tear. This finding suggests that alterations in mechanical loading may interfere with age-dependent muscle atrophy (Chapter 6).
- One year after RC repair, the operated shoulder reveals more glenohumeral elevation and less scapulothoracic lateral rotation than before surgery (Chapter 7)
- Latissimus dorsi or teres major tendon transfers are surgical options to improve pain and shoulder function in the treatment of a massive posterosuperior RC tears.

FUTURE PERSPECTIVES

Since the publication of our long-term outcomes of acromioplasty in 2017 in which we showed no beneficial effect of acromioplasty in SAPS (Chapter 2), more randomised controlled clinical trials have been published.[1, 36, 50] Consistent with our findings, no beneficial effect of acromioplasty was found. The emerging evidence have been recently adapted in some international guidelines and recommendations.[22, 33, 66, 67] These guidelines resulted in a decrease in the number of acromioplasties in the Netherlands from 2012 to 2016.[67] The upcoming years more work has to be done to prevent unnecessary subacromial decompression world-wide. The lack of evidence for surgical acromioplasty in patients with subacromial pain has still to be implemented in many other international guidelines. Because potential damage of subacromial tissues by attrition under the acromion may develop after many years as was hypothesised in our study, long-term follow-up data of other existing randomised controlled trials should be expected.[36] Moreover, a better selection of patients with subacromial pain may indicate that some patients are more likely to benefit from an acromioplasty or surgical intervention, for example by a better selection of patients based on anatomic characteristics.

The ineffectiveness of subacromial decompression will urge orthopaedic surgeons to develop a more effective ways to treat patients with SAPS. Our biomechanical and kinematical outcomes (Chapter 3) can be used to justify developments in physiotherapeutic interventions targeting glenohumeral rotations and muscle activation in SAPS when a causal role of our findings is assumed. A lower contribution of glenohumeral elevation and glenohumeral external rotation to the scapulo-humeral rhythm in SAPS may create a rational to study the effect of stretching exercises to increase glenohumeral rotations. Furthermore, the lower amount of teres major activity in SAPS during abduction (i.e. higher activation ratio) may rationalize the use of strengthening exercises of the teres major to increase humeral head depression during arm elevation. This treatment may aim to strengthen the teres major muscle to increase its antagonistic activity. Some current scientifically proven effective regimes already include a combination of stretching and strengthening exercises.[28] With the knowledge from this thesis, these physiotherapeutic regimes can be further developed.

In current orthopaedic practice, the finding "asymmetry in scapulothoracic motion" on itself has limited diagnostic value, although it gives an impression of pathology in the shoulder region. From a scientific perspective, clinicians have currently difficulty in correctly identifying an "alteration of normal kinematics" and the origin of this finding. This is illustrated by a comparable prevalence of asymmetric scapulothoracic motion in patients with and without shoulder pain if visual inspection is used.[34, 54, 65] Our study outcomes indicated a difference in shoulder kinematics between the asymptomatic and symptomatic shoulder in patients with SAPS, but it is unclear whether this difference reflects scapular dyskinesis or normal deviations between shoulders. Importantly, clinicians should be aware that "asymmetry in scapulothoracic motion" is not the same as "an alteration of normal kinematics".

First, we should define normal and pathologic scapulothoracic kinematics before it can be implemented in decision rules to correctly diagnose a patient. Quantitative methods (like three-dimensional motion capture) might be more accurate to distinguish normal from pathologic kinematics. The positive predictive value of small changes in shoulder rhythm alone or in combination with other physical tests has to be determined for various causes of shoulder pain. When we know normal and pathologic shoulder kinematics, we can implement quantitative methods in the clinical practice of physiotherapists and orthopaedic surgeons. Until then, we cannot confirm Codman's "*sine qua non*" statement for an RC tear, or accurately use scapular dyskinesis in the diagnosis of SAPS.

We identified an association between age and shoulder kinematic adaptation (Chapter 3). Since the intact RC muscles undergo a continuous decline in muscle mass (Chapter 6), the coordination of shoulder muscle activity can be expected to change during life. It is currently unknown, how muscle activity in the shoulder change during life. Age associated changes in muscle activity (e.g. teres major) and changes in thoracic posture due to intervertebral disc degeneration may importantly influence shoulder kinematics. The association between age and shoulder kinematics may play a role in the development of shoulder pain. This consideration was the rationale to separate patients with subacromial pain based on age, the younger patient with shoulder pain involved in repetitive overhead (sport) activities under the age of 35 years and patients with potential signs of RC degeneration between 35 and 60 years of age.[12] In the group of patients aged between 35 to 60 years, we postulated several pathophysiological pathways contributed to SAPS.

The SISTIM project aimed to categorise patients with SAPS based on pathophysiological mechanisms in a highly selected, and thus a homogenous, group of patients. Learning from the SISTIM project, future researchers should be aware of essential disadvantages when creating a more homogenous sample based on patient characteristics and anatomic substrate for pain. The initial goal was to include 108 patients, but unfortunately only 40 patients were included. Many exclusions were the result of the strict inclusion criteria and the shift of usual care Magnetic Resonance Imaging with arthrography (MRA) towards standard ultrasonography. Because usual care MRA was part of our inclusion protocol, numerous patients with SAPS did not become eligible for the SISTIM cohort limiting the generalizability of our data to the entire group of patients with subacromial pain. Although part of the SAPS syndrome according to the current concept, patients with biceps tendinopathy, acromioclavicular osteoarthritis and calcifying tendinopathy have been excluded conform the study protocol.[12, 14] Similarly, it is likely that patients with a glenohumeral internal rotation deficit (GIRD) were excluded from the SISTIM study. By applying the inclusion and exclusion criteria, we might have missed patients who are currently treated as SAPS. It is questionable that all patients with biceps tendinopathy, radiographic signs of acromioclavicular osteoarthritis or calcifying tendinopathy belong to a separate entity with its own pathophysiology for developing shoulder pain.

In future research, a slightly different approach is proposed to identify and classify distinct pathophysiological mechanisms in SAPS. A cross-sectional study like the SISTIM should include all patients clinically labelled as SAPS to improve generalizability of study outcomes. All patients should be exposed to the same type of additional imaging (e.g. MRA) as part of the research protocol and this imaging should not depend on the physician's judgement. The physician's criteria for making an MRA introduces a potential selection bias. Next, the exclusion of patients based on radiologic findings, also potentially limits generalizability of the study outcomes when such imaging doesn't have clinical consequences for treatment. These anatomic findings are interesting factors to categorise the patient with subacromial pain. Dissimilar biomechanical and kinematic patterns among patients with or without a radiologic anatomic finding suggests that a different pathophysiologic pathway for developing shoulder pain is involved.

A possible causal role of reduced glenohumeral external rotation and higher teres major activation ratio in the development of SAPS (Chapter 3) can be tested by evaluating the presence of shoulder pain in volunteers who are exposed and non-exposed to these biomechanical and kinematical factors. A possible approach is to participate in a project like the Rotterdam study.[27] In such a project a prospective cohort of participants is recruited generating big data. The recruited participants are interviewed and examined on possible causes of the disease at baseline. Patients are subsequently followed for years with periodical interviews, examinations of modifiable parameters and the evaluations for the presence of disease. For SAPS or for musculoskeletal diseases in general, determinants like patients' anatomy using MRI (e.g. segmented muscle volumes), shoulder biomechanics (e.g. posture, muscle coordination) and kinematics should be measured at baseline and during follow-up. Subsequently, exposure to anatomic-, biomechanical- and kinematical parameters can be identified as risk factors for disease by comparing controls with patients who developed subacromial pain. A design as used in the Rotterdam study could provide more answers regarding the causal role of glenohumeral rotations and muscle activation in the pathophysiology of (subgroups with) SAPS.

Next to anatomic, biomechanical and kinematical factors, the role of biological or genetic determinants in intrinsic pathways which facilitate RC degeneration have to be explored. Degenerative processes can make the RC more vulnerable for inflammation (i.e. SAPS) or rupture, and may cause secondary changes under the acromion.[8, 9, 13] This concept is consistent with historical observations suggesting that articular side tendon thickening and hyperplasia precede an RC tendon rupture.[13] Unfortunately, this finding has been overlooked for many years. The higher prevalence of RC tears among siblings compared to controls may also suggest an intrinsic aetiology or even genetic predisposition, although studies on genetic susceptibility for RC tendinopathy are scarce.[24, 55, 63] Moreover, the structure of the collagenous tendon is exposed to the age-associated decline in muscle mass and function of the contractive part of the muscle. With less muscle strain, the tendon potentially become more prone to inflammation and disorganization of tendon filaments.[47] The age-associated changes in muscle mass are thought to be prompted by several biological factors including the loss of motor neurons (i.e. denervation), physical activity, muscle adipogenesis, nutrition (e.g. protein or vitamin D deficiency), changes in extracellular matrix architecture, hormonal changes (e.g. insulin-like growth factor, myostatin) and immunological changes (e.g. interleukin).[15, 37, 47] Focus on the processes involved in muscle ageing may (partially) elucidate the causes contributing to a painful shoulder and the predisposition of the RC tendons to rupture.

Some authors suggest that an increase in neural signaling within the central nervous system is present in patients with SAPS.[21] The presence of central sensitization may clarify why some patients with only limited structural damage in the shoulder experience severe pain and functional limitations. Investigating the role of central pain sensitization and coping with shoulder pain may help to improve our understanding of chronic shoulder pain and may contribute to a more optimal use of treatment in shoulder patients.[21, 57]

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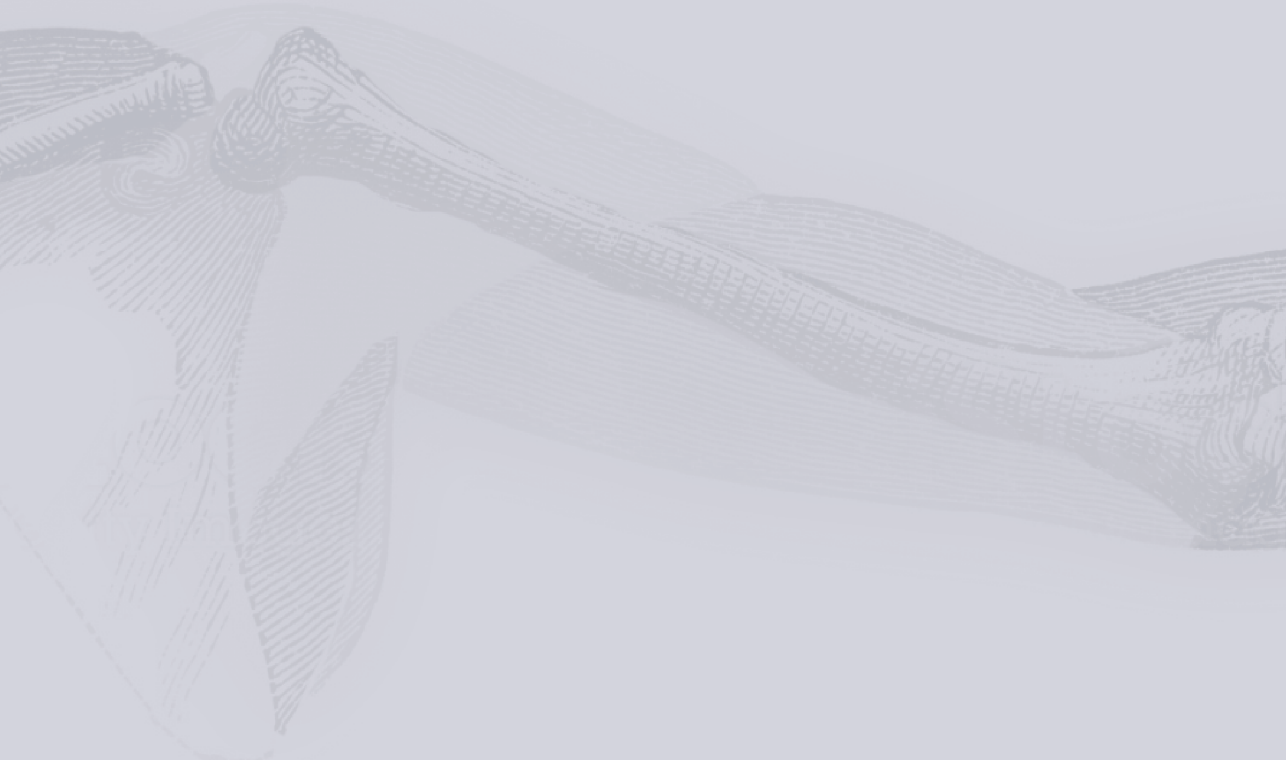

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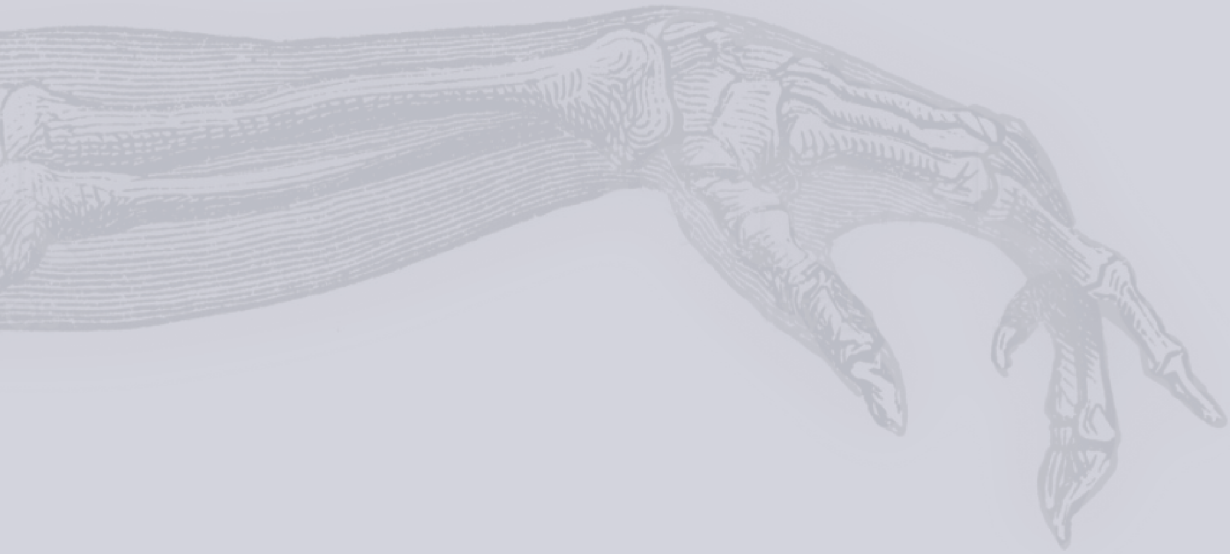
Summary in Dutch

Nederlandse Samenvatting



De schuingedrukte woorden worden nader toegelicht in de verklarende woordenlijst.
De verklarende woordenlijst is terug te vinden aan het einde van de samenvatting.

In **hoofdstuk 1** wordt een algemene introductie gegeven over het onderwerp. De schouder is na lage rugklachten de meest frequente locatie van *musculoskeletale* pijnklachten. De grootste groep patiënten met schouderpijn is tussen de 30 en 65 jaar. Zij worden vaak gediagnosticeerd met een aandoening die in de volksmond slijmbeursontsteking wordt genoemd. De diagnose is gebaseerd op een set van symptomen en het bewegingsonderzoek. De typische klachten van deze patiënten bestaan uit pijn, die verergert bij het heffen van de schouder en een onvermogen om op de aangedane schouder te kunnen liggen. Bij aanvullende diagnostiek hebben niet alle patiënten een onderscheidend radiologisch beeld, zoals vocht in de slijmbeurs of een *tendinitis*. Omdat de oorzaak van de pijn niet duidelijk is, spreken we tegenwoordig over het *subacromiaal pijn syndroom*.

Er is in het verleden veel onderzoek gedaan naar de potentiële oorzaken van het *subacromiaal* pijn syndroom. Jarenlang werd gedacht dat *impingement* van de schouderspieren onder het *acromion* de oorzaak zou zijn van de pijn. De pijn zou veroorzaakt worden door excessieve wrijving van pezen onder het *acromion* waardoor een chronische slijmbeursontsteking ontstaat met een *tendinitis*, en uiteindelijk als gevolg een *rotator cuff* scheur. Daarom werd het *subacromiaal* pijn syndroom voorheen *subacromiaal impingement* syndroom genoemd. Door een *bursectomie* met een *acromionplastiek* dachten chirurgen de excessieve wrijving onder het *acromion* te kunnen verminderen en de pijn te verlichten. De *acromionplastiek* werd de standaard orthopedische behandeling voor patiënten met een chronische "slijmbeursontsteking". Hoewel deze behandeling jarenlang werd verricht, waren er tot voorkort weinig goede onderzoeken die de effectiviteit van de operatie aantoonden. Onderzoek naar het effect en dus ook het falen van chirurgie door middel van een *acromionplastiek* geeft ons belangrijke informatie over hoe mensen met het *subacromiaal* pijn syndroom het beste behandeld kunnen worden.

Verschillende onderzoekers wezen ook op andere potentiële oorzaken die bijdragen aan het *subacromiaal* pijn syndroom. De irritatie en pijn kan veroorzaakt worden door een *degeneratief* proces van de pezen of door repeterende kleine traumatische beschadigingen van de pezen. Bovendien kan een dynamische verkleining van de ruimte onder het *acromion* leiden tot een compressie en pijnvolle irritatie van de *subacromiale* structuren. De dynamische verkleining zou kunnen optreden door *scapula dyskinesie* of door *translaties* in het *glenohumerale gewricht* als gevolg van een *rotator cuff* scheur.

In de literatuur zijn er veel studies te vinden die spieractiviteit en *kinematica* in schouders met *subacromiale* pijn bestuderen. In deze studies werden vaak specifieke groepen onderzocht, zoals jonge atleten met bovenhandse sporten of bouwvakkers met veel bovenhands werk, waardoor de *generaliseerbaarheid* van deze data naar de orthopedische praktijk beperkt is. Bovendien werd in het meeste onderzoek de diagnose "*subacromiale* pijn syndroom" gesteld zonder aanvullende radiologische beeldvorming. Patiënten met een typische radiologische diagnose (e.g. *rotator cuff* scheur) werden meegenomen in het onderzoek, terwijl een gescheurde pees de uitkomsten van de *kinematica* en *biomechanica* zal beïnvloeden. Het onderzoek naar spieractiviteit en *kinematica* geeft nieuw inzicht in de dynamische factoren die aanwezig zijn bij patiënten met het *subacromiaal* pijn syndroom. Daarnaast laat dit onderzoek naar de *kinematica* bij patiënten met een *rotator cuff* scheur het verband zien tussen de grootte van een *rotator cuff* scheur en het veranderde bewegingspatroon.

ONDERZOEK NAAR HET EFFECT VAN EEN ACROMIONPLASTIEK

In **hoofdstuk 2** van dit proefschrift wordt het effect van een *acromionplastiek* op pijn en schouderfunctie in de behandeling van patiënten met het *subacromiaal* pijn syndroom bestudeerd. In deze studie worden de lange termijn resultaten (9 tot 14 jaar na de operatie) beschreven van een studie, waarbij patiënten met het *subacromiaal* pijn syndroom een *bursectomie* of een *bursectomie* met een *acromionplastiek* kregen. Naast pijn en schouderfunctie werd er gekeken of er in de loop van de tijd een *rotator cuff* scheur was ontstaan. Uit dit onderzoek bleek dat beide groepen een verbetering hadden in pijn en schouder functie, welke vergelijkbaar waren met den resultaten uit het bestaande *cohortonderzoek*. Er kon dus geen effect van een *acromionplastiek* aangetoond worden. Daarnaast werd er geen verschil gevonden in het percentage patiënten met een *rotator cuff* scheur. Deze resultaten waren vergelijkbaar met onze eerdere resultaten 2.5 jaar na de interventie. In 2018, toonden twee grote *gerandomiseerde* onderzoeken eveneens aan dat een *acromionplastiek* niet leidt tot betere resultaten in de behandeling van een patiënt met chronisch *subacromiaal* pijn syndroom. Deze onderzoeken hebben geleid tot aanpassingen in de richtlijnen wereldwijd. Momenteel is het advies van de Nederlandse Orthopaedische Vereniging om een *acromionplastiek* niet als standaardbehandeling te verrichten voor het *subacromiaal* pijn syndroom.

BIOMECHANICA EN KINEMATICA IN PATIËNTEN MET HET SUBACROMIAAL PIJN SYNDROOM

In **hoofdstuk 3** wordt de spieractiviteit en de *kinematica* vergeleken tussen patiënten met het *subacromiaal* pijn syndroom en *asymptomatische* proefpersonen. Spieractiviteit werd uitgedrukt als ratio tussen *agonistische* en *antagonistische* activiteit. In patiënten met het *subacromiaal* pijn syndroom was er relatief minder *antagonistische* activiteit van de *teres major* dan in *asymptomatische* proefpersonen. Tijdens een aparte bewegingsregistratie vonden wij een lager aandeel *glenohumerale elevatie* en hoger aandeel *scapulothoracale* *laterorotatie* in de totale *thoracohumerale elevatie* van de arm. Daarnaast was er minder *glenohumerale exorotatie* tijdens *elevatie* van de arm.

Om deze resultaten te duiden is het belangrijk om de functie van de *teres major* te kennen. De trekrichting van de *teres major* werkt primair als *adductor* werkt. *Biomechanische* studies laten zien dat de *teres major* ook een *caudaal* gericht *moment* kan leveren op de *humerus*. De *teres major* heeft daarom ook een stabiliserende rol om *translaties* in het *glenohumerale* gewricht te voorkomen.

Op basis hiervan is onze hypothese over de relatie tussen schouder-stabilisatie en het *subacromiaal* pijn syndroom ontwikkeld. Minder *antagonistische* activiteit van de *teres major* betekent dat er een lagere activiteit van de *teres major* wordt gevonden tijdens het uitoefenen van krachten die *thoracohumerale elevatie* van de arm veroorzaken. Dit verlies aan kracht van de *teres major* leidt tot een verminderde schouder-stabilisatie, waardoor er meer translaties kunnen optreden. Het gevolg kan een dynamische verkleining van de *subacromiale* ruimte zijn. Tevens verklaart deze hypothese dat *glenohumerale elevatie* minder bijdraagt aan de totale *thoracohumerale elevatie*. Een minder stabiel centrum van rotatie in het *glenohumeraal* gewricht bij patiënten kan resulteren in compensatoire *scapulothoracale laterorotatie*. Eerder onderzoek heeft ook aangetoond dat *glenohumerale exorotatie* de *subacromiale* ruimte vergroot. Indien een patiënt zijn arm minder zal exoroteren in het *glenohumerale* gewricht, zal de *subacromiale* ruimte dynamisch kleiner zijn en wordt het contactoppervlak met de *subacromiale* structuren groter. Ook kan de verminderde *exorotatie* een gevolg zijn van een chronische *subacromiale* ontsteking met verlittekening van de slijmbeurs waardoor de *glenohumerale* mobiliteit vermindert. De bevindingen in dit hoofdstuk duiden op dynamische factoren die een rol kunnen spelen in het *subacromiaal* pijn syndroom.

In **hoofdstuk 4** onderzochten wij of er sprake is van asymmetrie in het *scapulothoracale* bewegingspatroon bij patiënten met het *subacromiaal* pijn syndroom. In de literatuur worden er verschillen tussen de aangedane en niet-aangedane schouder gevonden. Deze verschillen in *kinematica* kunnen optreden als gevolg van pijn, maar het bewegingspatroon zou ook bij kunnen dragen aan het ontwikkelen van pijn. Daarom onderzochten wij door middel van een experimentele studie wat de gevolgen zijn van een *subacromiale* infiltratie met pijnstilling (met het middel "lidocaïne") op de *kinematica* in de aangedane schouder van patiënten met het *subacromiale* pijn syndroom. In deze studie vonden wij meer *scapulothoracale interne rotatie* in patiënten met het *subacromiaal* pijn syndroom, maar vonden wij geen verschil in *scapulothoracale laterorotatie* en *scapulothoracale posterieure kanteling*. In tegenstelling tot onze verwachting werd het asymmetrische *scapulothoracale* bewegingspatroon niet symmetrisch na een *subacromiale* infiltratie, maar werd het zelfs nog meer afwijkend ten opzichte van de niet-aangedane zijde. Na infiltratie werd er meer *scapulothoracale interne rotatie* en minder *scapulothoracale posterieure kanteling* gevonden. Dit bewegingspatroon verkleint de *subacromiale* ruimte en lijkt daarom eerder ongunstig bij patiënten met *subacromiale* pijn. Een verklaring zou kunnen zijn dat pijn eerder een protectief effect heeft dan dat pijn bijdraagt aan een afwijkend bewegingspatroon.

BIOMECHANICA EN KINEMATICA BIJ EEN ROTATOR CUFF SCHEUR

In **hoofdstuk 5** wordt een verband gezocht tussen de grootte van een *rotator cuff* scheur, als maat voor de anatomische schade die aanwezig is in de schouder, en de *kinematica*. We weten uit computersimulaties en onderzoek op kadavers dat de *infraspinatus* belangrijk is voor de *glenohumerale* stabiliteit. Een insufficiënte *infraspinatus* kan leiden tot *craniale translatie* van de *humerus*, waardoor er geen stabiel rotatiepunt meer is voor beweging in het *glenohumerale* gewricht. Bij patiënten met schouderklachten was nog nooit aangetoond dat de grootte van de *rotator cuff* scheur geassocieerd is met de *kinematica*. Uit ons onderzoek blijkt dat patiënten met een zeer grote *rotator cuff* scheur (waarbij zowel de *supraspinatus* pees als de *infraspinatus* pees gescheurd zijn) minder *glenohumerale elevatie* hebben dan patiënten zonder scheur of met een kleinere *supraspinatus* scheur. Gelijktijdig wordt er een vergelijkbare toename van de *scapulothoracale laterorotatie* gezien in de patiënten met een zeer grote *rotator cuff* scheur. Vanwege de associatie tussen de grootte van de *rotator cuff* scheur en de *kinematica*, heeft kwantitatieve bewegingsregistratie objectieve diagnostische waarde.

In **hoofdstuk 6** wordt aangetoond dat er een verband bestaat tussen de aanwezigheid van een *rotator cuff* scheur en de hoeveelheid *atrofie* van de andere intacte spieren in de schouder. *Atrofie* werd gemeten door middel van het meten van de dwarsdoorsnede op MRI's van patiënten met klachten aan de schouder. Gemiddeld 3 jaar na de eerste MRI hadden de patiënten een tweede MRI-onderzoek ondergaan. De dwarsdoorsnede meting werd gebruikt als afgeleide van spiervolume. Gebruikelijk is dat het spiervolume boven de 35 jaar in de schouder geleidelijk aan afneemt. Echter, patiënten met een *rotator cuff* scheur hadden een minder grote achteruitgang in spiervolume (i.e. *teres minor* en *deltoideus*) dan patiënten waarbij de gehele *rotator cuff* nog intact was. Bij sommige patiënten met een gescheurde *supraspinatus* pees werd zelfs een toename van de spier dwarsdoorsnede gezien. De associatie tussen een gescheurde *supraspinatus* pees en de dwarsdoorsnede meting van de spieren was het grootst in patiënten onder de 50 jaar. Met dit onderzoek werd indirect het effect van een gescheurde *supraspinatus* spier voor het krachtenspel in de schouder beschreven. Volgens de resultaten van eerder *biomechanisch* onderzoek met computermodellen zouden deze *teres minor* en de *deltoidius* meer krachten moeten leveren indien er een scheur in de *supraspinatus* pees aanwezig is. Dit onderzoek kan verklaren waardoor patiënten met een groter spiervolume van de *teres minor* betere functionele resultaten hebben bij een massale *rotator cuff* scheur of na een omgekeerde schouder prothese.

KINEMATISCHE EN KLINISCHE UITKOMSTEN NA EEN OPERATIE

In **hoofdstuk 7** wordt de *kinematica* van de schouder beschreven vóór en nadat een scheur in de *rotator cuff* chirurgisch is hersteld. Tevens wordt deze *kinematica* vergeleken met de bewegingen van de niet aangedane schouder. Na herstel van de *rotator cuff* is er een toename in de *glenohumerale elevatie* en een afname in de *scapulothoracale laterorotatie*. De *kinematica* na de operatie is beter vergelijkbaar met de manier van bewegen van de niet aangedane schouder. Terwijl de schouderfunctie na een herstel van de *rotator cuff* doorgaans met *semi-kwantitatieve* methoden wordt onderzocht, worden in dit hoofdstuk voor het eerst kwantitatieve methoden gebruikt om de veranderingen in de *kinematica* en range of motion na een herstel van de *rotator cuff* aan te tonen.

In **hoofdstuk 8** worden de resultaten van een operatie, waarbij het verloop van een pees (de *teres major* of de *latissimus dorsi*) wordt verplaatst, beschreven ter behandeling van een grote *rotator cuff* scheur. Indien het technisch niet meer mogelijk is om de *rotator cuff* chirurgisch te herstellen en het plaatsen van een prothese nog wordt ontraden (dus niet geïndiceerd is), bestaat er een indicatie voor het verplaatsen van de spier (ook wel “transpositie” genoemd). Het doel van de spierverplaatsing is om de schouderfunctie te verbeteren door zowel een effect op het heffen van de arm als een effect op de *exorotatie*. Deze *exorotatie* is belangrijk om de arm naar het hoofd en de mond te kunnen brengen of om de haren te kammen. Tussen 2003 en 2007 had de *teres major* transpositie de voorkeur in het Leids Universitair Medisch Centrum, van 2007 tot 2010 was de *latissimus dorsi* transpositie de eerste keuze. In dit hoofdstuk beschreven wij de resultaten van de behandeling gemiddeld 10 jaar na een *teres major* transpositie en gemiddeld 6 jaar na een *latissimus dorsi* transpositie. Terwijl de *latissimus dorsi* transpositie tegenwoordig vaker wordt toegepast en het resultaat van de operatie vaker is onderzocht, is onze studie de eerste studie die de lange termijn resultaten van de *teres major* transpositie laat zien. Patiënten na een *teres major* transpositie hadden op de lange termijn nog steeds een vermindering van pijn en verbetering van functie ten opzichte van voor de operatie. Ook bij patiënten na een *latissimus dorsi* transpositie werd nog steeds een vermindering van pijn en verbetering van functie gevonden. Momenteel is het de vraag welke van deze twee spieren het best gebruikt kan worden voor een spier verplaatsende operatie (i.e. transpositie). De *teres major* heeft als *biomechanisch* voordeel dat deze spier na de transpositie een vergelijkbaar anatomisch beloop krijgt (namelijk van de *scapula* naar de *humerus*) als de gescheurde *rotator cuff* spier. Onze resultaten laten zien dat de *teres major* transpositie een alternatief is voor de *latissimus dorsi* transpositie. Inmiddels is er een *gerandomiseerd* onderzoek opgezet om te onderzoeken welke van de twee operaties de beste biomechanische, kinematische en klinische resultaten geeft.

In **hoofdstuk 9** wordt een samenvatting van alle resultaten gegeven en wordt bediscussieerd wat deze resultaten voor de patiënt met schouderklachten in de toekomst kunnen betekenen. De belangrijkste conclusies uit het onderzoek worden herhaald. Tot slot wordt de manier waarop toekomstig onderzoek bij zou kunnen dragen aan onze kennis over het *subacromiaal* pijn syndroom uiteengezet.

VERKLARENDE WOORDENLIJST

Acromion: Deel van het schouderblad dat het schouderdak vorm.

Acromionplastiek: Een orthopedische operatie waarbij de onder en voorzijde van het schouderdak (i.e. *acromion*) deels wordt verwijderd.

Adductor (schouder): Een spier die een kracht uitoefent op de bovenarm zodat de arm naar het lichaam toe beweegt.

Agonist: Een spier die met een beweging de grootste kracht levert om de beweging te maken door samen te trekken. Antoniem van *antagonist*.

Antagonist: Een spier die in de beweging een tegenovergestelde werking heeft als de *agonist*. Antoniem van *agonist*.

Asymptomatisch: Een persoon zonder symptomen van een ziekte.

Atrofie: Hiermee wordt de afname in de omvang van weefsel bedoeld, in dit geval de afname in spiervolume.

Biomechanica (schouder): Het toepassen van natuurkundige mechanica bij de studie naar de structuur, vorm en functie van de bewegingen in de schouder.

Bursectomie: Operatie waarbij de slijmbeurs (i.e. bursa) verwijderd wordt.

Caudaal: In het Latijn betekent cauda “staart”. In de anatomie duidt het de richting van de voeten aan (i.e. omlaag).

Cohortonderzoek: Dit is een methode van onderzoek waarbij een groep mensen worden gevolgd in de loop van de tijd. Alle mensen die voldoen aan vooraf gedefinieerde eigenschappen worden meegenomen. Problemen die zich voordoen wanneer het effect van een behandeling wordt onderzocht zijn onder andere onwillekeurige selectie en het natuurlijk beloop van een ziekte. Immers, de gevolgen van een ziekte verandert met de tijd (bijvoorbeeld de meeste verkoudheden genezen zonder behandeling). Daardoor is het effect van een behandeling lastig te meten.

Craniaal: In het Latijn betekent craniaal “de schedel”. In de anatomie duidt het de richting van het hoofd aan (i.e. omhoog).

Degeneratief: Een proces van *degeneratie* duidt een geleidelijke achteruitgang van functie of structuur in de loop van de jaren aan.

Deltoideus: De grote driedelige spier en de spier die de meeste krachten levert om de arm in het *glenohumerale* gewricht te heffen.

Exorotatie: Met de bovenarm naast het lichaam, draait de bovenarm om zijn lengteas van het lichaam af. In deze positie draait de arm naar “buiten”. Deze term wordt in de orthopedische praktijk gebruikt.

Generaliseerbaarheid: De mate waarin de steekproef van de studie ook geldig is voor de algehele populatie.

Glenohumeraal: Het gewricht tussen schouderblad en de bovenarm. De naam is afgeleid van het gewrichtsoppervlak van het schouderblad (i.e. glenoid) en de bovenarm (i.e. *humerus*).

Glenohumerale elevatie: Een term die gebruikt wordt om de beweging in de schouder te beschrijven. Om de stand tussen twee botdelen te beschrijven wordt om elk bot een coördinatensysteem gedefinieerd. In dit geval tussen de *scapula* en de *humerus*. De *Glenohumerale elevatie* geeft de rotatie om een as weer waardoor de arm kan worden geheven, terwijl de positie van de *scapula* gelijk blijft.

Glenohumerale exorotatie: Een term die gebruikt wordt om de beweging in de schouder te beschrijven. Om de stand tussen twee botdelen te beschrijven wordt om elk bot een coördinatensysteem gedefinieerd. In dit geval tussen de *scapula* en de *humerus*. *Glenohumerale exorotatie* geeft de draaiing om de lengteas aan. De draaiing is van het lichaam af, terwijl de positie van de *scapula* gelijk blijft. De beweging vindt plaats om de lengteas van de *humerus* welke loopt van de schouder richting het ellebooggewricht.

Humerus: de bovenarm.

Infraspinatus: De musculus *infraspinatus* is één van de vier spieren van de *rotator cuff* en hecht aan de boven-achterzijde van de bovenarm aan. Deze spier wordt verantwoordelijk gehouden voor de *exorotatie* van de schouder.

Impingement: Hiermee wordt inklemming van anatomische structuren onder het schouderdak bedoeld waardoor excessieve wrijving onder het *acromion* zou ontstaan. Aangezien het bewijs voor deze wrijving beperkt is, is deze term verouderd en wordt er tegenwoordig in Nederland niet meer gesproken over het *subacromiaal impingement* syndroom.

Kinematica (schouder): De *kinematica* is een onderdeel van de *biomechanica* waarbij gekeken wordt naar de bewegingen zonder het bestuderen van onder andere krachten en *momenten*.

Latissimus dorsi: De *latissimus dorsi* is de grote brede rugspier. De spier hecht via een peesblad aan op de onderzijde van de ruggenwervels en aan de andere zijde hecht hij aan op de bovenarm (i.e. humerus).

Moment: Een *moment* is een term uit de mechanica, waarbij het rotatie-effect van een kracht op een object wordt aangeduid.

Musculoskeletaal: Verwijst naar de spieren en botten.

Randomiseren: Dit is een experimentele onderzoeksmethode die wordt gebruikt in *cohortonderzoek* waarbij de effectiviteit van twee of meer behandelingen worden vergeleken (e.g. medicatie of chirurgische behandelingen). Bij *randomisatie* worden patiënten volstrekt willekeurig op basis van het lot verdeeld over verschillende groepen. Op deze manier probeert de onderzoeker de selectie van patiënten te voorkomen. Onwillekeurige selectie is in wetenschappelijk onderzoek een probleem omdat het dan onzeker is of het verschil in uitkomst gerelateerd is aan de te onderzoeken behandeling of aan de onwillekeurige selectie. Immers, bij onwillekeurige selectie kan het verschil in uitkomst ook veroorzaakt worden door bepaalde eigenschappen die de ene groep wel heeft, maar de andere groep niet.

Rotator cuff: De *rotator cuff* wordt gevormd door vier spieren en omsluiten de kop van de bovenarm (i.e. *humerus*) in de schouder. De *rotator cuff* bestaat uit de pezen van de subscapularis, *supraspinatus*, *infraspinatus* en *teres minor*. Al deze spieren “ontspringen” op het schouderblad en hechten aan op de bovenarm.

Scapula: Het schouderblad.

Scapula dyskinesie: “Elke afwijking van een normaal *scapulothoracaal* bewegingspatroon”. In de dagelijkse praktijk van de orthopedie wordt doorgaans bij een asymmetrie van *scapulothoracale* bewegingen gesproken over *scapula* dyskinesie.

Scapulothoracaal: Hiermee wordt de relatie tussen het schouderblad (i.e. *scapula*) en de borstholte (i.e. thorax) aangeduid.

Scapulothoracale interne rotatie: Een term die gebruikt wordt om de beweging in de schouder te beschrijven. Om de stand tussen twee botdelen te beschrijven wordt om elk bot een coördinatensysteem gedefinieerd. In dit geval tussen de *scapula* en de borstholte (i.e. thorax). De beweging vindt plaats om de as die in staande positie (ongeveer) verticaal door de *scapula* loopt. Bij deze beweging vindt om deze as beweging naar het lichaam toe plaats, terwijl de positie van de thorax gelijk blijft. Een ander woord voor *scapulothoracale interne rotatie* is protractie.

Scapulothoracale laterorotatie: Een term die gebruikt wordt om de beweging in de schouder te beschrijven. Om de stand tussen twee botdelen te beschrijven wordt om elk bot een coördinatensysteem gedefinieerd. In dit geval tussen de *scapula* en de borstholte (i.e. thorax). De beweging vindt plaats om de as die in staande positie (ongeveer) horizontaal van achteren naar voren loopt. Bij deze beweging vindt er om deze as beweging plaats richting het hoofdeinde, terwijl de positie van de thorax gelijk blijft. Een ander woord voor *scapulothoracale laterorotatie* is “upward rotatie”.

Scapulothoracale posterieure kanteling: Deze kanteling wordt ook posterieure tilt genoemd. Een term die gebruikt wordt om de beweging in de schouder te beschrijven. Om de stand tussen twee botdelen te beschrijven wordt om elk bot een coördinatensysteem gedefinieerd. In dit geval tussen de *scapula* en de borstholte (i.e. thorax). De beweging vindt plaats om de as die in staande positie (ongeveer) horizontaal van links naar rechts loopt. Bij deze beweging vindt om deze as een naar achteren (posterieur) gerichte draaibeweging plaats, terwijl de positie van de thorax gelijk blijft.

Semi-kwantitatief: Dit duidt op eigenschap van de methode waarmee gemeten wordt. Een kwantitatieve uitkomst geeft weer dat de uitkomst gemeten wordt in absolute en min of meer continue aantallen. *Semi-kwantitatieve* uitkomsten geven een benadering van de aantallen. De aantallen kunnen worden weergegeven met intervallen en zijn de uitkomsten niet continue.

Subacromiaal: Duidt een plek aan welke onder het schouderdak (i.e. *acromion*) gelegen is.

Subacromiaal pijn syndroom: Dit is een schouderaandoening waarbij verondersteld wordt dat de schouderpijn afkomstig is vanuit de *subacromiale* weefsels. Verschillende radiologische afwijkingen worden gewonden bij dit syndroom zoals een slijmbeursontsteking (i.e. bursitis) of een peesontsteking (i.e. tendinitis). Deze aandoening heette voorheen het subacromiaal impingement syndroom omdat men dacht dat excessieve wrijving de oorzaak van de pijn was.

Supraspinatus: De musculus *supraspinatus* is één van de vier spieren van de *rotator cuff* en hecht aan bovenop de *humerus*. De spier draagt bij aan het heffen van de bovenarm.

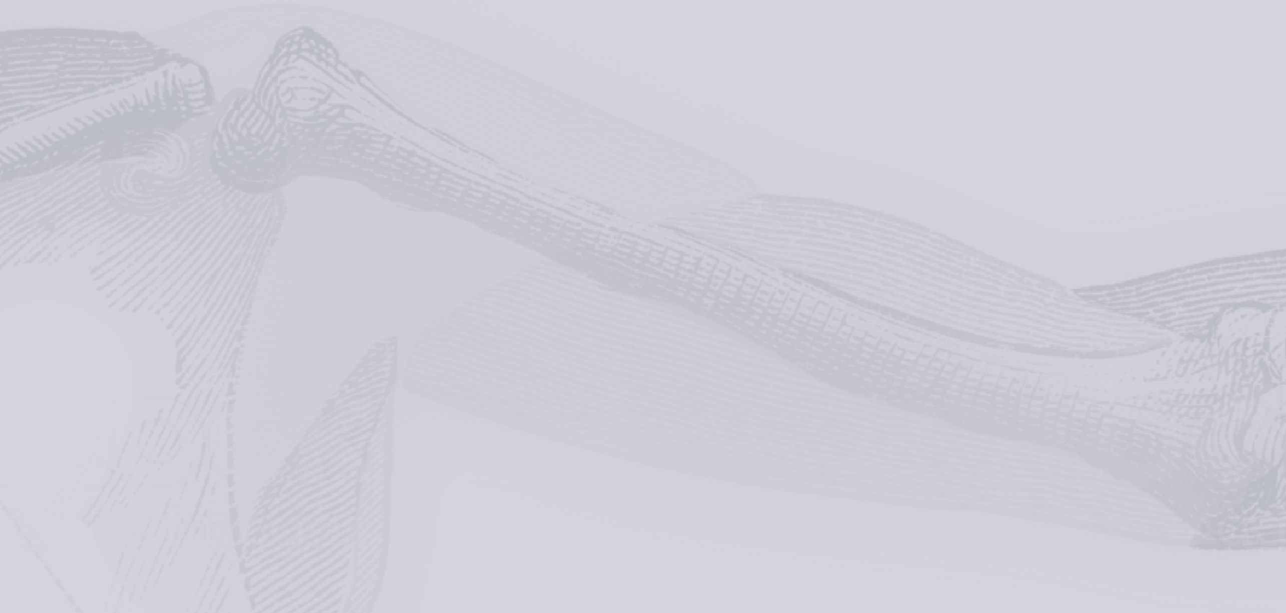
Tendinitis: Ontsteking van een pees.

Teres major: De musculus *teres major* is de grote ronde armspier aan de achterkant van de schouder. De spier hecht aan op het schouderblad en de bovenarm.

Teres minor: De musculus *teres minor* is één van de vier spieren van de *rotator cuff* en hecht aan op de achter-onderzijde van de *humerus*.

Thoracohumerale elevatie: Een term die gebruikt wordt om de beweging in de schouder te beschrijven. Om de stand tussen twee botdelen te beschrijven wordt om elk bot een coördinatensysteem gedefinieerd. In dit geval tussen de *humerus* en de borstholte (i.e. thorax). Tijdens deze beweging wordt de arm geheven (i.e. elevatie).

Translatie: Een verplaatsing van een object in de ruimte. Alle punten van het object hebben dezelfde verplaatsing ondergaan, waardoor de oriëntatie van het object in de ruimte behouden blijft. Indien ook de oriëntatie verandert, vindt er een rotatiebeweging plaats.



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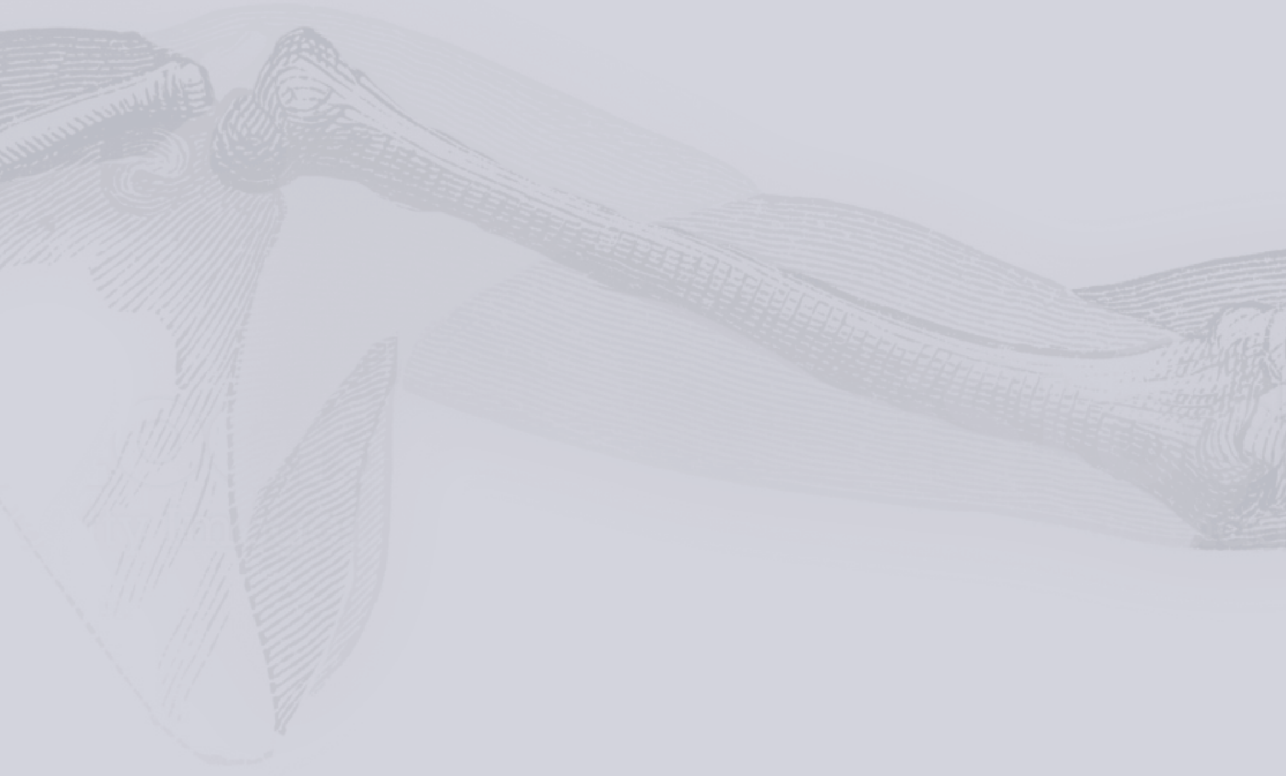

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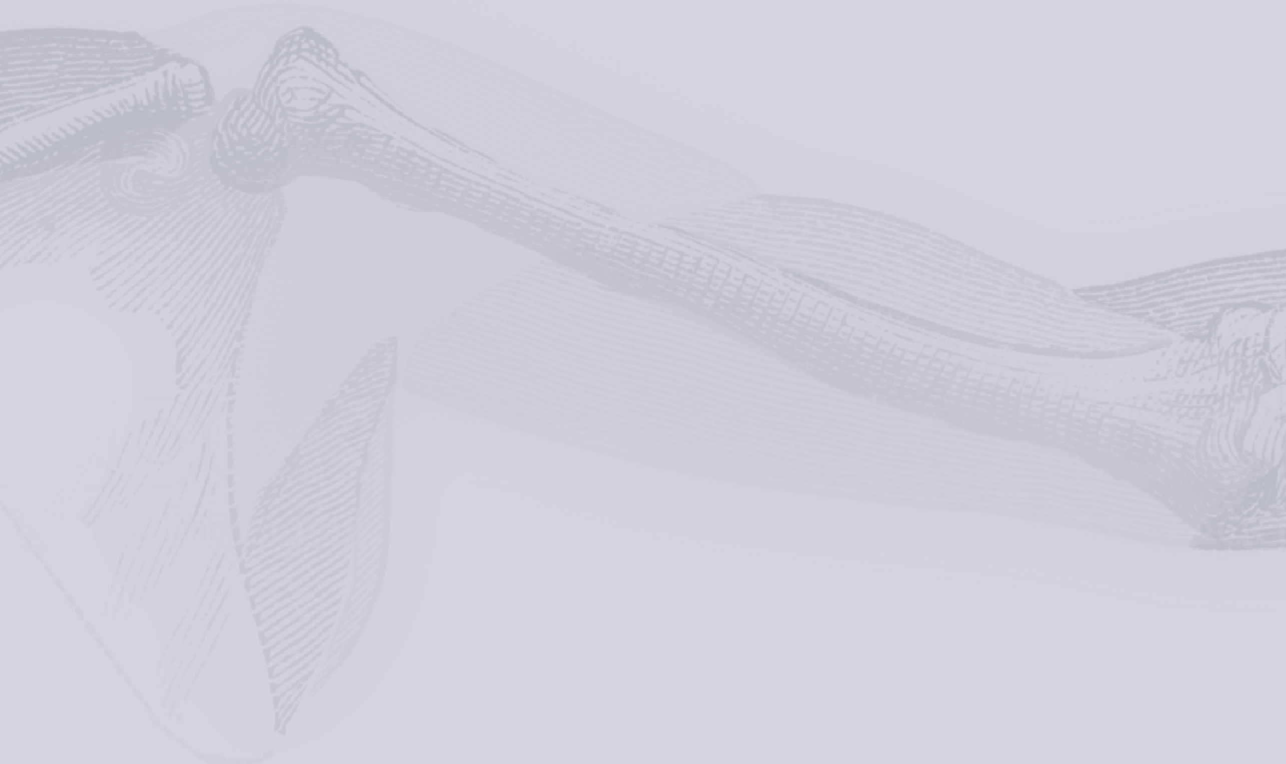
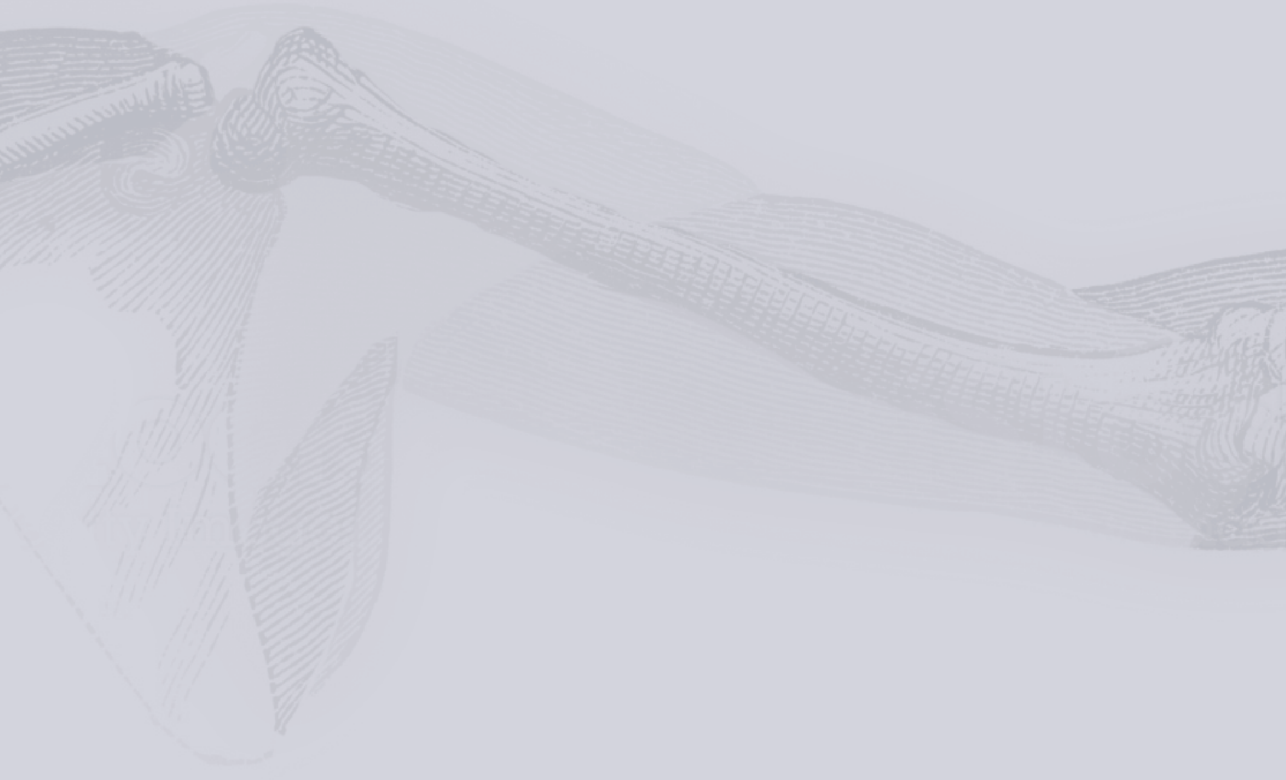


Curriculum Vitae

Arjen Kolk was born on September 2nd 1986 in Utrecht, the Netherlands. He obtained his gymnasium diploma at the Oosterlicht college, Nieuwegein in 2004. The same year, he was admitted to study medicine at the Utrecht University. After completing medical school in 2010, he worked three years as a non-training resident in surgery at the St. Antonius Hospital in Nieuwegein/Utrecht (supervisor dr. Peter Go) and orthopaedic surgery at the Alrijne Hospital in Leiderdorp (supervisor dr. Cornelis Visser). His clinical observations and participation in shoulder research contributed to his passion for science to improve orthopaedic health-care. He started a PhD-trajectory on subacromial pain syndrome at the Leiden University Medical Centre in 2013 under supervision of dr. Jochem Nagels, assistant-professor dr. ir. Jurriaan de Groot, and professor dr. Rob Nelissen. The results of this project are described in this thesis. In January 2017, he started his general surgery residency at the department of surgery at the St. Antonius Hospital in Nieuwegein/Utrecht (supervisor dr. Djamila Boerma) as part of his training as Orthopaedic surgeon. Since July 2018 he worked as a training resident in orthopaedic surgery at the Haaglanden Medical Centre, the Hague (supervisor Ewoud van Arkel) and Leiden University Medical Centre, Leiden (supervisor professor dr. Rob G.H.H. Nelissen).



Dankwoord

Geachte professor dr. Nelissen, beste Rob, dank je wel voor het onuitputtelijke enthousiasme, waardoor de zoektocht naar nieuwe kennis altijd een feest is geweest. Je stimuleerde mij om de bewijsvoering van de vele orthopedische gewoontes kritisch tegen het licht te houden.

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Cornelis Visser, Ewoud van Arkel, Peer van der Zwaal, Anna Navas Cañete en Monique Reijnierse, dank jullie wel voor de gedeelde passie voor het wetenschappelijk onderzoek en onze samenwerking. Samenwerken is een erg belangrijke voorwaarde om wetenschappelijk onderzoek te doen, of het nu gaat om de inclusie van patiënten of een radiologische beoordeling.

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Ing Han, Jelle, Jonathan, Niels en Tim. De pool- en bieravonden zijn zoveel meer dan alleen een vriendschap. Tijdens deze avonden deelden wij op een humoristische wijze onze visies, waardoor wij elkaar (onbedoeld) ook hielpen in onze professionele ontwikkeling. Ik ben dankbaar dat onze vriendschap blijft bestaan nu we verspreid door heel Nederland wonen.

Margan en Wouter. Ik weet nog heel goed waar onze vriendschap als leden van werkgroep 8 begon. Onze etentjes (met de geweldige boeuf bourguignon), de zeilweekenden en fietstochten hebben mij zoveel gebracht. Met jullie heb ik mijzelf ontwikkeld als persoon en dokter. Beste Wouter, door jouw analytisch vermogen was zelfs de sympathische activiteit in chronische nierziekten interessant en durfde ik mijn eerste wetenschappelijke stappen te zetten. Dank je wel.

Lieve papa en mama. Jullie hebben altijd laten zien mijn grootste fan te zijn. Jullie hebben ervoor gezorgd dat ik alle kansen kreeg om mijn talenten zowel op muzikaal, sportief als maatschappelijk vlak te ontwikkelen. Hierdoor bleef ik mijn grenzen opzoeken. Jullie zijn voor mij een voorbeeld.

Menno. Het is wonderbaarlijk hoe erg verschillend twee broers kunnen zijn. Maar juist door deze verschillen werd ik uitgedaagd om aandacht te besteden aan andere vaardigheden. Vaardigheden die heel belangrijk zijn. Daarom wil ik benadrukken: samen opgroeien is samen leren. Ik kan oprecht stellen dat dit proefschrift zonder jou niet had bestaan. Dank je wel dat jij mijn broer bent!

Lieve Chantal. Ik ben ontzettend dankbaar voor de tijd die je mij hebt gegund om dit proefschrift af te ronden. Daarom is dit werk een echte teamprestatie. Samen met jou is het leven zoveel leuker en kunnen we genieten van het aller dierbaarste, onze Mats en straks zijn broertje of zusje.