MANAGEMENT OF IRREPARABLE SUBSCAPULARIS TENDON TEARS

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CONTENTS

I grew up with an ambition and determination without which I would have been a good deal happier. I thought a lot and developed the far-away look of a dreamer, for it was always the distant heights which fascinated me and drew me to them in spirit. I was not sure what could be accomplished by means of tenacity and little else, but the target was set high and each rebuff only saw me more determined to see at least one major dream through to its fulfillment.

Earl Denman, Alone to Everest

1 INTRODUCTION

The first description of an isolated subscapularis tendon tear is attributed to Gerber and Krushell.[1] The authors noted that clinical diagnosis of subsapularis tears remains a challenge and they described the so-called lift-off sign as a reliable clinical sign for the diagnosis of subscapularis insufficiency. In a subsequent follow-up of his experience Gerber reported on the midterm results after repair of the subscapularis tendon. He observed that repairs of chronic subscapularis tears had a much poorer outcome than repairs performed in an acute setting. [2]

The anterosuperior cuff tear configuration, which represents a tear of the subscapularis in combination with the supraspinatus and sometimes the infraspinatus, was first recognized as a discrete entity by Warner et al. .[3] The authors observed, in the same way as Gerber, that tears involving the subscapularis often had a delayed diagnosis which resulted in late presentation of the patients for treatment.

Indication for reconstruction of chronic subscapularis tears by tendon tranfer are not yet fully established. All considerations must be placed in the context of the patients disability and their expectations for pain relief and functional recovery. Many factors like location of the tear, quality of the tendon tissue to repair, associated degenerative changes of the glenohumeral joint, number and nature of previous surgeries, age and compliance of the patient should be considered prior surgery. As this tear configuration occurs usually in younger and active patients, treatment in the chronic situation after delayed diagnosis is challenging, because recovery of function and strength is essential in this high demanding group of patients.

1.1 IRREPARABLE ROTATOR CUFF TEARS: DEFINITIONS AND THERAPEUTICAL PRINCIPLES

1.1.1 FATTY DEGENERATION AND ATROPHY OF THE ROTATOR CUFF MUSCLES

Structural integrity of the rotator cuff is a conditio sine qua non for normal shoulder function.[4-6] Although clinical results after repair of massive rotator cuff tears are frequently good [7,8], several studies have shown that structural healing does not reliably occur after technically successful repair of massive tears.[4,5,9]

During many years the principles in diagnosis and treatment of rotator cuff tears had focused on the tendinous defect and its reattachment to the bone only, without considering the effect of the tendon tear on the corresponding muscle.

The correlation between rotator cuff tear and a possible degeneration of the affected muscles, was described by Goutallier et al., 1989.[10] Based on standardized preoperative CT scan images of the shoulder of patients undergoing rotator cuff surgery, he defined a rating system describing a muscular degeneration of torn rotator cuff units. Histologically the degeneration was shown to correspond to an infiltration of the muscular substance by fat, the so called fatty degeneration. The comparable observations were made in a rabbit model. [11]

Another feature of the torn rotator cuff muscle, namely muscle atrophy, has been described on MRI by Nakagaki.[12] Zanetti et al. demonstrated that the degree of atrophy measured on cross-sectional aeras of standardized para-sagittal MRI images inversly correlates to the degree of fatty degeneration.[13]

Both fatty degeneration and atrophy have been shown to be an irreversible process in the animal and in humans after successfull structural repair of the tendon.[9,14,15] Furthermore, Gerber et al. demonstrated in a clinical study that degenerative muscular changes even may increase after repair suggesting that high tension resulting from reinsertion of a less elastic musculotendinous unit may worsen the state of degeneration of the affected muscle.[9]

Due to the irreversible loss of contractile properties of the repaired musculotendinous unit, weakness persists even after structural repair of the tendon. Furthermore advanced atrophy and fatty degeneration has been shown to be more often associated with retear when primary repair is attempted.[9,16] Up to now no scientific data are available, defining precisely at which stage of muscular degeneration and in which part of the rotator cuff primary repair of a torn tendon is still possibly. However clinical experience suggests that in the presence of fatty degeneration higher than Grade II according to Goutallier, an alternative to primary tendon repair should be considered, especially if recovery of function and strength is the goal of treatment.

Those observations have fundamentally changed the way to evaluate and treat rotator cuff tears in the last years. A rotator cuff tear is no longer an isolated tendinous pathology, but much more a disease of the whole musculotendinous unit. This is of utmost importance when surgical treatment is considered.

1.1.2 PATTERNS OF CHRONIC ROTATOR CUFF TEARS

Reparability

Rotator cuff tears involving two tendons or more are defined as massive tears. They are commonly associated with muscle atrophy and fatty degeneration of the corresponding muscles, leading to decrease in contractile properties of the musculotendinous units. As advanced atrophy and fatty degeneration appears to be irreversible and often associated with retear when primary repair is attempted, such tears are considered irreparable.

In rare cases, the quality of the tendon is so poor, even in absence of advanced degenerative changes of the muscle, that secure repair to the bone is not possible. Such tears are encountered in revision surgery and are also considered irreparable.

Configurations of irreparable rotator cuff tears

Irreparable chronic rotator cuff tears can be divided into several patterns showing a different epidemiology, associated disability and natural history.

Because they are small and do not tend to retract, isolated supraspinatus tears can usually be repaired reliably. In rare cases fatty degeneration and atrophy of the supraspinatus muscle and/or poor tendon quality can render a tear irreparable. As the remaining parts of the cuff are intact, the functional deficit remains moderate. Pain and decrease in abduction strength are the leading symptoms.

Disruption of the infraspinatus is always associated with a supraspinatus tear and has been defined as posterior-superior tears. Per definitionem those tears are massive involving at least two tendons, the supraspinatus and infraspinatus, and may extend into the teres minor. In some patients where the tears extend inferior to the equator of the humeral head, the force couple between the anterior and posterior part of the cuff is disrupted. The required force to stabilize and to maintain a fixed fulcrum for rotation of the humeral head in the glenoid during flexion or abduction is insufficient. Functionally this leads to a superior migration of the humeral head and a decrease in abduction and flexion. Due to the insufficient infraspinatus, the strongest external rotator of the glenohumeral joint,[17] those tears make movement of the hand to mouth or to the head difficult.

Isolated ruptures of the subscapularis are less frequent than supraspinatus or anteroposterior rotator cuff tears. Because unspecific complaints like pain and weakness without severe loss of function are in most cases the only clinical signs, subscapularis tears are underdiagnosed and treatment mostly occurs with delay. Then reconstruction of the tendon may not be possible anymore due to fatty degeneration and atrophy of the subscapularis muscle.

Anterosuperior tears are subscapularis tears involving the subscapularis and the supraspinatus tendons. They are even less common than isolated subscapularis tears and usually painful and disabling. Together with global tears, the represent a therapeutic challenge.

Tears involving both the anterosuperior and the posterosuperior portions of the rotator cuff are often associated with degenerative changes of the joint. They are defined as rotator cuff tear arthropathy.[18] Painful limitation of motion is the leading symptom.

1.1.3 SURGICAL APPROACHES TO IRREPARABLE ROTATOR CUFF LESIONS

Irreparable rotator cuffs have not been considered as a single group in the evaluation of conservative treatment for rotator cuff tears. [19,20] Based on clinical experience, it appears that functionally compensated irreparable posterosuperior tears are relatively well tolerated. When pain becomes an issue, conservative therapy with strengthening of the intact portion of the rotator cuff may be an adequate therapeutic option, especially in the eldery patient. Irreparable subscapularis and anterosuperior tears are usually resistant to conservative treatment. However unremitting pain and/or decrease in function sometimes persit despite conservative treatment. Then surgery may be required. As mentioned above poor muscle and/or tendon quality does not allow reliable direct tendon to bone repair and alternative surgical techniques have to be considered.

Débridement and subacromial decompression

Arthroscopic débridement has been proposed for eldery patients whose main complaint is pain.[21-24] This technique however, fails to restore strength. [21,23] Durability of pain relief has been questioned by some authors[25,26], whereas others reported spectacular stable longterm results. [27]

Allografts and synthetic cuff implants

The attempt to bridge large rotator cuff defects with rotator cuff allografts [28] or synthetic rotator cuff patches[29] remained without reproducible results and never gained broad acceptance. Although the concept may appear very simple, it does obviously not solve the problem of the above discussed muscular disease in irreparable tears. For selected cases in which irreparability of the tear is caused by a specific tendon problem, tendon augmentation may be a suitable solution.

Rotator cuff advancement and transposition

To reduce tension at the side of repair, lateral advancement of the supraspinatus and infraspinatus musculotendinous units within the supra- and infraspinal fossa has been proposed to repair large rotator cuff tears.[30,31] As for rotator cuff allografts or synthetics, this kind of procedure does not address the problem of degenerative changes encoutered in irreparable rotator cuff tears.

Local tranposition of the subscapularis tendon to repair large tears has been proposed by Cofield.[32] As transposition seems to adversly affect active elevation, this technique has not found wide acceptance either.[33]

Fusion and resection arthroplasty

In patients with irreparable cuff tears, arthrodesis does not provide consistent pain relief.[34] Neither does resection arthroplasty. [34] These techniques are used in selective cases and are considered as ultimate salvage procedures.

Replacement arthroplasty

Constrained or unconstrained total shoulder replacement has been used in patients with irreparable rotator cuff tears. Due to eccentric loading early glenoid component loosening has been observed. [35-38]

Although good pain relief has been reported with conventional or bipolar humeral head replacement, functional results are unpredictable, especially when severe loss of function is present prior to surgery. [39-44] 1986, Grammont developed the so-called trumpet prosthesis to treat cuff tear arthropathies.[45] The clinical experience with this implant have shown superior functional results compared to hemiarthroplasty or bipolar arthroplasty .[46-49]

Tendon transfer procedures

A tendon transfer is defined as a procedure in which the tendinous insertion of a muscle is divided and reinserted to a bony part or another tendon to supplement or substitute for the action of a nonfunctioning musculotendinous unit.[17] The use of such procedures to treat irreparable rotator cuff tears is a relatively new field and the indications are not yet fully established. The clinical experience of several authors provides some guidelines and suggests that tendon transfer is a reliable option to treat symptomatic localized (anterosuperior or posterosuperior) irreparable rotator cuff tears in the abscence of articular changes of the glenohumeral joint.[50-57]

1.2 STRUCTURAL FUNDAMENTALS OF SKELETAL MUSCLE

1.2.1 STRUCTURAL MODELS

The exact nature of mechanical transduction within the skeletal muscle has not yet been fully elucidated. The understanding of the transformation of a neural signal into a force producing muscle contraction is based on two different stuctural models that have evolved over the years. The first type of models, based on Hill´s empirical work[58,59], results in a higher-order nonlinear model considering three independent experimentally measured factors which describe the length-tension property, the force-velocity property and the dynamics of activation by neural imputs. The effects of simplifications characterizing such a model on the understanding of muscle behaviour during movement, have never been adequately quantified. However, eighth order Hill based antagonistic muscle-joint models have been used successfully to describe the biomechanics of complex joints, like the knee joint. [60]

The second type of models is based on the structure and chemistry of muscle, describing excitation-contraction coupling and contraction dynamics.[61] They result in complex partial differential equations.

The advantages and disadvantages of both types of models are still a matter of debate. For clinical purposes, it is important to have a capability to simulate human movement without modifying model parameters for different tasks. Brand´s approach to muscle properties is a simple and clinically useful synthesis of essential structural and biomechanical features of the skeletal muscle.[62] Although the model does not consider ultrastuctural and biochemical features of human muscle, Brand was able to validate his concept in experimental and clinical work. Furthermore the data arising from Brand´s experiments on muscle properties, are considered as basic knowledge in tendon transfer surgery of the forearm and the hand.[62]

1.2.2 CONTRACTILE MECHANISM

The sliding filament theory

Current understanding of the basic mechanisms of skeletal muscle contraction is based on the sliding filament theory proposed by Huxley.[61] Muscle contraction occurs due to the interaction between actin and myosin muscle proteins, wich are arranged along with other structural and regulatory proteins in a regular pattern: the sarcomere.

Within each sarcomere, actin molecules form the thin filaments and the myosion molecules (thick filaments) carry regular spaced crossbridges along their length, giving a typical and constant pattern to all sarcomeres regardless which muscle is considered.

Sarcomeres are arranged in series to build myofibrils and to provide the needed muscle excursion. Furthermore the myofibrils are arranged in parallel to form the muscle bulk and generate the needed force.

The transduction of the neural signal into a contraction is a complex biochemical process, involving the release of acetylcholin at the neuromuscular junction, the calcium and ATP metabolisms within the cell and leading to a confomational change of the contractile filament and finally to a contraction. The details of the muscular contractile mechanism are still matter of debate.

Viscoelastic properties of skeletal muscle

The viscoelastic properties of a muscle arises from muscle contractile properties and the passive properties of non-contractile tissue within the muscle and are used to the describe the general relationship between muscle force and displacement and can be used to describe muscle behaviuour when either forces or displacement are imposed.

Although viscoelasticity is a term used to describe all aspects of muscle responses to mechanical disturbances, specific aspects have recieved more attention than others , probably due to their simplicity. Elasticity (or stiffness) describing the length-to-force relationsship and viscosity describing the velocity-to-force properties are the most relevant aspects for clinical applications.

The tension-length relationship

The amount of force generated by a muscle is known to depend upon its length. Indeed the sliding filament theory hypothetizes that changes in sarcomere length due to contraction or external loads result in different amounts of overlap between the thick filament containing crossbridges and the thin filament containing active binding sites.[63-65] Although animal studies suggest that the length-tension properties of each sarcomere within a single muscle may vary, they are often similar enough to assume that the length-tension curve of the whole muscle has similar features. The generated force increases with length up to a certain point, remains on a plateau and then declines. (Fig.1)

The tension generated by the sarcomere reaches its maximum at the resting length. This maximum force will be maintained for even shorter lengths until the thin filament on the opposite ends of the sarcomere begin to overlap and interfere with force generation. Clinically the peak strength of an active muscle contraction will occur when the muscle is approximately in the middle of its total range between maximal stretch and full contraction.

If a muscle is streched to the point that there is no more overlap between the filaments, no force can be generated. On the other hand in the fully contracted sarcomere the overlap of the thin filaments will reduce force generation. (Fig.1)

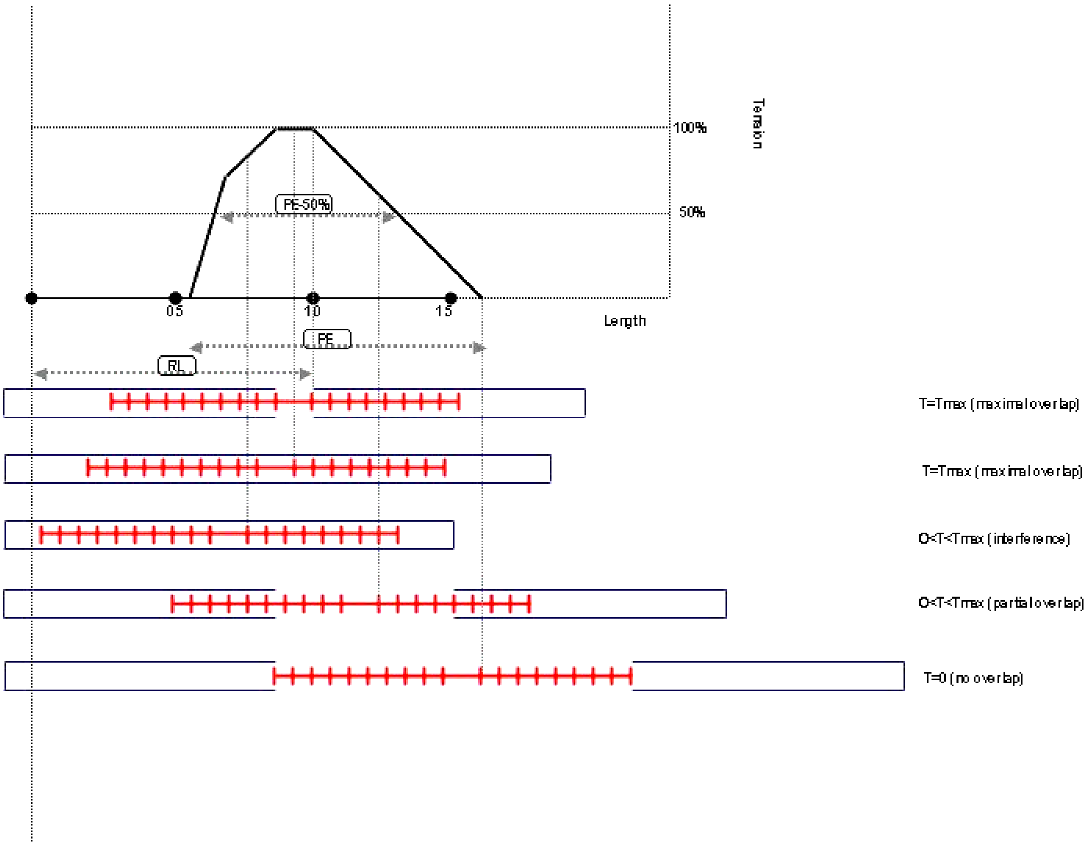

Figure 1: The tension-length curve

The resting length (distance RL) is defined as the length of the sarcomere (or the muscle fiber) at which all the cross-bridges are within binding proximity to an actin active site.[62,66] Clinically this occurs when the limb is in its resting and balanced condition.

An important feature is the relationship between the resting length (distance RL) of the sarcomere and its potental excursion (distance PE), defined as the distance between the stretched length and the fully contracted length. Brand et al. observed that RL and PE are approximatively of equal length.[62] Therefore a sarcomere (or a muscle fiber) will be able to contract actively from maximal stretch to maximal contraction through a distance approximatively equal to its resting length. For example: a muscle fiber measuring 10 cm in the resting position could have an excursion of about 10 cm.

It is important to note that at each end of the excursion the generated tension would be almost zero. In addition the distance PE-50% indicates the potential excursion of a muscle within a range of at least 50% of its maximal tension.

The force-velocity relationship

The length-tension curve arises from an unatural status, in which the muscle length is experimentally determined and force is measured after supramaximal stimulation. In most activities, the muscle is either allowed to shorten or forced to lengthen by external loads. It has been recognized that the amount of force produced by the a given muscle for a fixed activation level depends on the speed the muscle length is changing and on the direction. In contrast to the length–tension relationship, which results primarily from the amount of overlap between the filaments, the force-velocity relationship arises primarily from cross-bridging cycling dynamics.

In the shortening muscle the maximum force is developed for zero velocity, i.e. for isometric conditions. As shortening velocity increases, the force drops in a hyperbolic fashion.[58] The mechanisms acting to produce force-velocity properties during lengthening are basically different from those produced during shortening. Lengthening of a stimulated muscle is the result of an external load imposed which is greater than the force generated through contraction. The lengthening muscle always can generate more strength than the isometric contracting muscle. When the external load exceeds 1.2-1.8 times the maximal force generated in the isometric condition, the resistance against movement does not increase anymore. This phaenomenon is known as muscle yielding. At loads exceeding the elastic properties of the muscle fibers and the passive non-contractile elements, structural damage within the muscle tissue may occur.

It is important to note that the relationship described is based on measurements with maximally activated muscles under constant loading conditions. The shape of the force-velocity curve for the whole muscle in vivo has been shown to depend on the activation level and to dependent on previous movement history.[67,68]

Neural control of muscle contraction

All muscle properties required to maintain posture and produce movement are modified by change of the activation level which is initiated by the motoneuron group of the muscle. Although the process is complex and non-linear, it can be assumed that an increase in the activation level of single muscles leads to increases in stiffness and force. It is important to realize that control of limb posture, and movement is the result of a global and organized pattern of activation of all muscles involved. Therefore the transfer of a musculotendinous unit will require adaptation of the whole neural control system. This explains the long postoperative rehabilitation phase after structural healing of the transferred unit. Further description of the complex neural control mechanisms of limb mouvement and posture is beyond the scope of this work.

1.2.3 RELEVANCE OF MUSCLE CAPABILITIES IN TENDON TRANSFER SURGERY

According to Brand, a muscle considered for transfer should match the dysfunctional recipient unit in regard of excursion, strength and orientation, so that its functionality can be restored. [62,69]

Potential excursion

The change in length - the exursion - that can be produced by a muscle is an important measure of its suitability for transfer. Indeed when a muscle is transferred, the required excursion in its new location may be different and may even be beyond the elasticity it can deliver.[69]

In vitro measurements

Assuming that all sarcomeres within a muscle are identical and that the resting length of one sarcomere is equal to its potential excursion, Brand postulated that the variable that characterizes a muscle must be be related to the sarcomere in series, the fiber length. He concluded that the average fiber length of a muscle is proportional to the potential excursion from the fully contracted to the fully streched muscle fiber. In fresh cadavers and under standardized conditions he measured the fiber length of the forearm muscles below the elbow and listed their potential excursion.[62]

In his comprehensive study Herzberg reported on the potential excursion of the main thirteen muscles of the shoulder girdle using Brand´s methodology.[17]

In vivo measurements

Freehafer et al. determined the potential excursion of the forearm muscles in vivo (so-called available excursion), considering both active and passive muscle properties.[70] Their study showed a poor correlation between the potential excursion measured in vivo and the available exursion. Furthermore they found out that passive streching of a muscle only accounts for approximatively one third of the total available excursion of the tendon, while the remaining two thirds are resulting from active contraction. Finally they were able to show that soft tissue dissection around the muscle to be transferred significantly increases the available amplitude of the muscle. Although the durability of this effect is not known, it appears that surgical release around the transferred unit is warranted to increase the available excursion.

Another approach to determine muscle length in vivo has been proposed by Lieber et al.. In their study sarcomere length of flexor carpi ulnaris and extensor carpi radialis brevis muscles was measured intraoperatively using a laser diffraction device. The sarcomere length operating range varied between the muscles. Furthermore the sarcomere length of the flexor carpi ulnaris was different after transfer onto the extensor carpi brevis.

The available excursion of the shoulder muscles is not known.

Strength

Although a muscle can be strengthen by exercice or may show atrophy due to inactivity, the relative strength of a muscle within a given functional muscle group remains fairly constant .[62]

To determine the relative strength of the forearm muscles Brand used following equations:

$$rm = A \times rv \quad (1)$$

Where:

- rm is the relative mass (kg),
- $A=1.02$ kg/cm^3 and is the density of skeletal muscle as determined by Mendez and Keys[71] and
- rv is the relative volume (cm^3).

$$rc = rv/fl \quad (2)$$

Where

- rc is the relative cross-section (cm^2)
- fl is the mean fiber length (cm)

From equation (1) and (2) follows:

$$rc = rm / A \times fl \quad (3)$$

As the muscles can be weighted and the fiber length measured, the relative cross-section area of a group of muscles can be calculated by equation (3).

Furthermore, the cross-section of a muscle is proportional to the maximal tension it can generate.[62] Therefore the relative tension of each muscle of a group of muscles can be calculated by equation (3).

In his study Herzberg analysed the relative strength of the shoulder girdle muscles.[17]

Force vector orientation

Estimation of the contribution of a muscle to the maximum isometric moment developed about a joint depends on severel accurate estimates; the muscle operating range on its tension-length curve, its physiological cross-section, and its moment arm. In tendon transfer surgery matching force vector orientation between the transferred and the dysfunctional muscle is a difficult task. The muscles available for transfer for a given dysfunctional musculotendinous unit are limited and their anatomical arrangement is usually very different from the muscle they should replace. Furthermore the moment arm of a transferred muscle may change and become less favourable because the position of the limb is changing. Clinical methods for analysis of the movement patterns after palsy or selective nerve blocks, movement analysis using electrophysiologic methods as well as calculation of moment arms in mechanical or geometric models has been proposed for a better understanding of the biomechanical effect of the muscles around the shoulder joint. However the kinematic of tendon transfer procedures around the shoulder has not yet been comprehensively described.

1.3 TENDON TRANSFER PROCEDURES AROUND THE SHOULDER

1.3.1 OVERVIEW ON CLINICAL EXPERIENCE

Restoration of muscle balance around the shoulder has been first described by L'Episcopo 1934.[72] He did his research for a group of children with obstetrical plexus palsy and chose following tendon transfer procedure for treatment: the latissimus dorsi and teres major tendon were detached from the medial border of the humerus and reattached to its lateral border. This is changing the action of these muscles from internal rotators to external rotators. Consequently this is balancing the forces around the joint by weakening internal rotation strength and strenghtening external rotation strength.

The idea to perform a tendon transfer procedure for reconstruction an irreparable rotator cuff is attributed to Mikasa 1984.[73] He proposed to transfer the trapezius for reconstruction of massive rotator cuff tears. The results of this technique remained unreproducible.

1985 a french group proposed the use of the anterolateral part of the deltoid for the reconstruction of irreparable lesion of the supraspinatus and infraspinatus.[74] Although this technique is routinely used in Europe and is known to provide good pain relief, the deltoid flap transfer is not leading to recovery of strength and has not been used in North America. Furthermore, this transfer jeopardizes the integrity of the deltoid muscle, which may compromise the outcome of further procedures, like the implantation of a reversed total shoulder arthroplasty.

The first promising report on tendon transfer for irreparable tears of the superior-posterior rotator cuff was published 1988 by Gerber.[75] He described the anatomical basis and first clinical results of the latissimus dorsi transfer for irreparable tears of the supraspinatus and infraspinatus and he presented overall outstanding longterm results 1992.[50] Since then similar successful results with this method have been reported.[51,52,76]

The trapezius transfer has been proposed to compensate for irreparable tears of the subscapularis, but it has not become an established method.[77] Wirth and Rockwood reported good and excellent results with the pectoralis major transfer for irreparable ruptures of the subscapularis.[53] Vidil and Augereau reported successful transfer of the clavicular part of the pectoralis major for the same pathology, emphasing, however that weakness persisted despite improvement in function.[78] In order to mimic the line of action of the subscapularis, Resch has proposed to reroute the tendon of the pectoralis major underneath the conjoined tendon[54] and Warner has described the split pectoralis major procedure in which the clavicular part of the pectoralis major is rerouted underneath its sternal part.[79]

1.3.1.1 Tendon transfer procedures for irreparable subscapularis and anterosuperior tears

Only few studies have analysed the management of the irreparable subscapularis tendon tears. The original description of pectoralis major transfer by Wirth and Rochwood is considered as the gold standard for irreparable ruptures of the subscapularis.[53] Although pain relief is usually achieved with this transfer, recovery of strength does not reliably occur with this procedure.[53,57] From the biomechanical point of view the pectoralis major has an adequate excursion and strength. However the line of action of the pectoralis transfer may not be optimal because it is directed anteriorly to the coronal plane, whereas the subscapularis force vector points posteriorly.

In order to improve the line of action of the transfer, Resch et al. described a technique in which the upper part of the pectoralis major is rerouted underneath the conjoined tendon. In their opinion this would give a more favorable line of action for the transfer compared to the traditional technique. However major concern with this approach is the risk of injury of the musculocutaneous nerve, especially in the setting of failed prior surgery with extensive scarring. Although the complication rate with this version of the transfer is not higher than with the conventional transfer, short term results do not seem to be superior to those achieved by Wirth et al and Jost et al. In order to improve the line of action of the transferred pectoralis major without jeopardizing the musculoskeletal nerve, Warner proposed to reroute the sternal head of the pectoralis major underneath its intact clavicular head and to fix it to the greater tuberosity.[55]

1.4 SCIENTIFIC OBJECTIVES OF THE MONOGRAPH

In the following chapters new anatomical, biomechanical and clinical aspects relevant to the surgery of irreparable subscapularis tears are discussed. All chapters have the structure of scientific papers and some of them could already been submitted for publication.

Anatomy

Subscapularis tears should be released and repaired whenever the quality of the muscle allows primary repair. During surgery the neurovascular structures can be damaged. This may represent an anatomical constraint for circumferential release and direct repair. Intraoperative guidelines helping the surgeon to localize the subscapular nerves have not yet been clearly defined. Now the purpose of ***Chapter 2.1*** is to describe the surgical anatomy of the subscapularis nerves and to define surgical guidelines.

The pectoralis major transfer is considered as the gold standard in the treatment of irreparable subscapularis tears. However the force vector orientation of this transfer may not be optimal in comparision to the situation at the subscapularis muscle. Anatomical studies suggest that the subscapularis muscle can be divided in two main components, the upper or thoracic part of the muscle respectively the lower or axillary part.[80] Based on its location as well as on innervation and function, the teres major muscle turns out to be an optimal candidate for selective reconstruction of the lower part of the suscapularis muscle. It is the objective of ***Chapter 2.2*** to describe the specific anatomy and surgical technique of the teres major tendon transfer for selective reconstruction of the lower subscapularis.

Biomechanics

As discussed in the introduction, a muscle considered for transfer should match the dysfunctional recipient unit with respect to strength, excursion and orientation, in order to restore muscle balance and eventually function of the joint. Whereas potential excursion and relative tension of the shoulder girdle muscles are known[17], detailled analysis of the vector orientation of the normal cuff and especially of common tendon transfer procedures around the shoulder have not yet been reported.

The purpose of ***Chapter 3.1*** is to define a three dimensonal cadaveric model which allows vector calculation of the shoulder girdle muscles.

More specifically the purpose of ***Chapter 3.2*** is to calculate the vector orientation of different transfer procedures for treatment of irreparable subscapularis tears using the model defined above. In addition, a comparision is made between the vectors of the transferred muscles and the original vector of the subscapularis musculotendinous unit.

Clinical considerations

Finally, based on the acquired anatomical and biomechanical data, ***Chapter 4.1*** describes a new surgical concept for the treatment of irreparable subscapularis tears and reports on the early clinical experience in a series of 7 patients.

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2 ANATOMY

2.1 THE SUBSCAPULAR NERVES ARE ANATOMICAL CONSTRAINTS TO CIRCUMFERENTIAL RELEASE OF THE SUBSCAPULARIS MUSCLE[1]

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2.1.1 INTRODUCTION

Circumferential mobilization of the subscapularis muscle is an important step in reconstructive shoulder procedures, like repair of subscapularis or anterosuperior rotator cuff tears, shoulder arthroplasty, revision instability surgery or open capsular release. The subscapularis muscle is shortened in such pathologies due to chronic rupture of the tendon or longstanding limitation of external rotation. In absence of advanced degenerative muscle changes, circumferential release of adhesions and mobilisation of the subcapularis is considered as an essential surgical step for direct repair.[1] The mobilization of the muscle includes release of adhesions at the upper border of the muscle, at the anterior surface between the conjoined tendon and the muscle, and along the scapular neck at the posterior surface of the muscle.[2]

The anatomic description of the subscapular nerves has been subject of several cadaveric studies.[3-7] Most of them are concentrating on detailled description of the subscapularis innervation without considering their surgical relevance. Checchia et al. and Yung et al. have been the first to describe the surgical anatomy of the subscapular nerves. [6,7] In shoulders with an intact subscapularis tendon they reported on the location of the subscapular nerves relative

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[1] Submitted to J. Shoulder Elbow Surg.

to the glenoid rim and showed that the nerve branches are at risk when the arm is externally rotated.

None of the studies mentioned above has described the position of the subscapular nerves after circumferential release and lateral mobilization of the subscapularis tendon.

It was the first objective of this study to evaluate the influence of subscapularis release and lateral traction on the postion of the subscapularis nerves relative to the coracoid process. And the second purpose was to define surgical guidelines to avoid injury of the neurovascular supply to the subscapularis muscle during release.

2.1.2 MATERIAL AND METHODS

Fifteen fresh frozen human cadaveric shoulders were thawed at room temperature for dissection. None of the donors had suffered rotator cuff pathology or had had previous injuries or surgical procedures performed on the shoulder joint. The skin was removed circumferentially and the deltopectoral interval identified. To expose the proximal third of the humerus, the deltoid muscle was detached from the clavicle and the anterolateral acromion. The tendon of the pectoralis major was identified and dissected sharply from the humeral shaft. Then the pectoralis major was dissected up to the clavicule and the pectoralis minor tendon was detached from the coracoid. To expose the infaclavicular portion of the brachial plexus, the neurovascular pedicles to the pectoralis major and minor muscles were sectioned. Then the medial border of the conjoined tendon was dissected and the musculocutaenous nerve identified. The conjoined tendon was detached from the coracoid and the musculotendinous unit removed after the musculocutaneous nerve had been sectioned at its entry point into the muscle.

In a next step attention was turned to the posterior part of the plexus. The dissection was performed from lateral to medial identifying and preserving every vascular and neural structures entering the subscapularis muscle. Then the subscapular nerves were dissected from the posterior part of the plexus and it became possible to record the number of branches including their ramifications and to mark the penetration area of each branch into the subscapularis muscle.

The rotator interval was identified and opened to visualize the upper border of the subscapularis and the base of the coracoid. A suture was fixed at the lateral border of the base of the coracoid and tightened inferiorly following the medial border of the scapula . Starting from the same point at the basis of the coracoid a second suture was placed perpendiculary to the first suture.

With the arm held in neutral position the vertical and horizontal distances between the lateral border of the base of the coracoid and the entry point of the subscapular nerves into the subscapularis muscle were measured using the two sutures as reference axis.

Finally the tendon of the subscapularis was detached from the lesser tuberosity and braided sutures were passed through the edge of the tendon in a modified Mason-Allen stich configuration. Using the sutures the tendon was pulled anteriorly to expose the articular part of the subscapularis muscle. The joint capsule was incised at the level of the labrum from the upper to the lower border of the subscapularis, simulating a circumferencial release. Then the tendon was pulled laterally and the horizontal and vertical distances between the lateral border of the coracoid and subscapular nerves were recorded as described above .

2.1.3 RESULTS

In all shoulders an upper, middle and inferior subscapular nerve branches could be identified. The nerve branches arose from the posterior cord of the brachial plexus in all shoulders with one exception. For this specimen, the inferior subscapular branch arose directly from the axillary nerve.

Figures 2a and 2b show the distribution of the subscapular nerve branches for all specimens and their relative position according to the lateral border of the coracoid before and after release of the subscapularis.

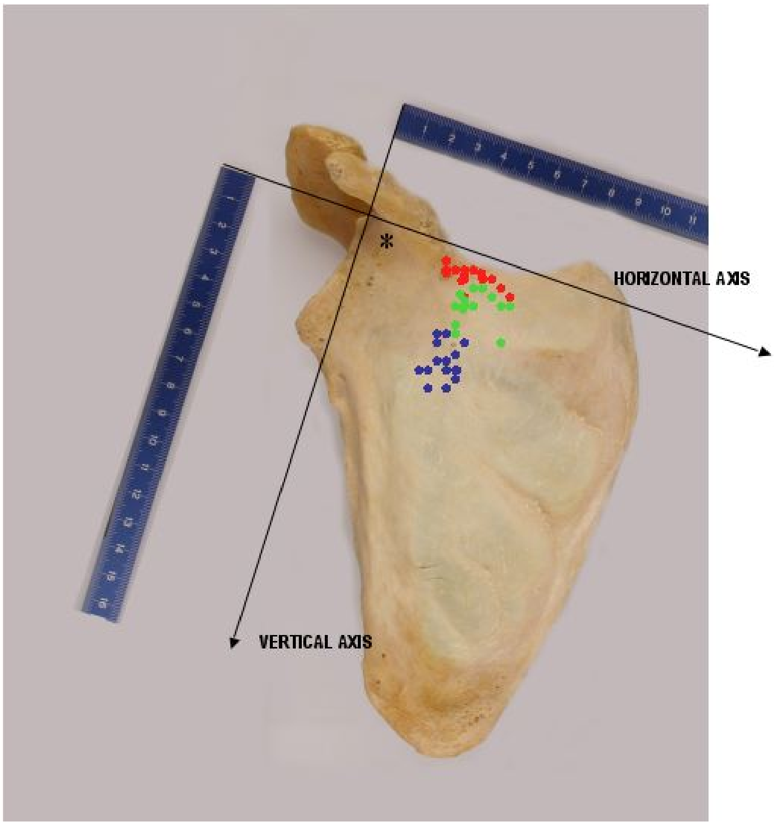

Figure 2a: Distribution of the nerve entry points before release of the subscapularis with the arm in neutral rotation. Red points: upper subscapular nerve branches; green points middle subscapular nerve branches; blue points lower subscapular nerve branches. Star:base of the coracoid process.

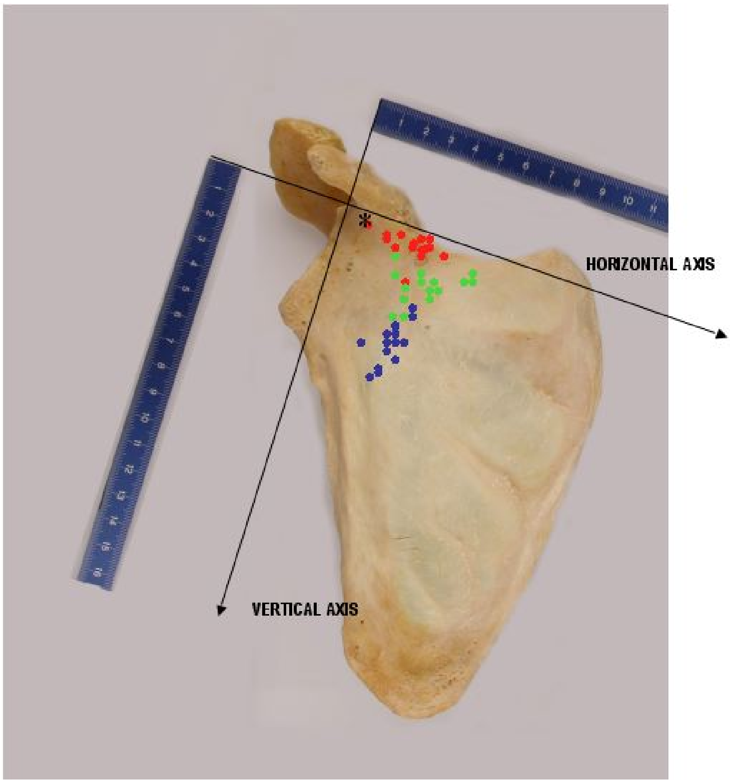

Figure 2b: Distribution of the nerve entry points after release of the subscapularis and lateral traction on the tendon. Red points: upper subscapular nerve branches; green points middle subscapular nerve branches; blue points lower subscapular nerve branches. Star:base of the coracoid process.

Table I below gives an overview of the measured distances for each group of nerve branches.

The mean horizontal distance between the lateral border of the coracoid and the most lateral ramification of the upper subscapular nerve group was 40.1 mm ± SD 9.2 mm (ranging from 25 mm to 55 mm) with the arm in neutral rotation. When the subscapularis was pulled laterally after release, the mean distance between the most lateral nerve branch and the lateral border of the coracoid process was 25.1 mm ±SD 9.0mm (ranging from 5 mm to 40 mm). This was significantly shorter than before the release (p<0.0001).

TABLE I: **Overview of the mean horizontal and vertical distances between the lateral border of the coracoid and the entry point of the subscapularis nerve branches into the suscapularis muscle**

	HORIZONTAL DISTANCE					VERTICAL DISTANCE§	
	Neutral rotation, subscapularis intact		Neutral rotation, subscapularis detached, released and pulled laterally				
	Mean±SD (mm)	Range (mm)	Mean±SD (mm)	Range (mm)	P value*	Mean±SD (mm)	Range (mm)
Upper subscapularis branch	40.1±9.2	25-55	25.1±9.0	5-40	<0.0001	10.6±5.0	2-25
Middle subscapularis branch	45.3±7.7	40-60	29.9±5.6	20-40	<0.0001	26.0±7.8	15-45
Lower subscapularis branch	45.2±10.9	35-80	30.0±6.5	15-45	<0.0001	46.3±8.6	34-62

* Determined with the Student t-test for paired correlated groups

§ No difference could be measured for the vertical distance before and after release with lateral mobilization of the subscapularis muscle

The mean horizontal distance between the lateral border of the coracoid and the most lateral ramification of the middle subscapular nerve group was 45.3 mm ± SD 7.7mm (ranging from 40 mm to 60 mm) with the arm in neutral rotation. When the subscapularis was released and pulled laterally this distance decreased to 29.9 mm ±SD 5.6mm (ranging from 20 mm to 40 mm) and this was significantly shorter than prior the release ($p<0.0001$).

The mean horizontal distance between the lateral border of the coracoid and the most lateral ramification of the lower subscapular nerve group was 45.2 mm ±SD 10.9 mm (range from

35 mm to 80 mm) with the arm in neutral rotation When the subscapularis was pulled leaterally this distance was 30.0 mm ±SD 6.5 (ranging from 15 mm to 45 mm) and this was again significantly shorter than prior the release ($p>0.0001$).

No difference could be measured before and after release with lateral mobilization of the subscapularis muscle. The mean vertical distance between the lateral border of the coracoid and the entry point of the most lateral ramification of the subscapular nerve branches was 10.5 mm ± SD 5.0 mm (range from 2 mm to 25 mm) for the upper subscapular nerve branch, 26.0 mm ± SD7.8 mm (range 15 mm to 45 mm) for the middle branch, and 46,3 mm ± SD 8.6 mm (range from 34 mm to 62 mm) for the lower branch.

2.1.4 DISCUSSION

Although the descriptive anatomy of the subscpular nerve branches was registrated during dissection, the main purpose of this study was to define surgical guidelines to avoid iatrogenic denervation of the subscpularis muscle during mobilization of the musculotendinous unit.

The position of the susbcapular nerve branches relative to selected anatomical landmarks has been described previously.[3-7] However only few of the points used as reference for measurements are easy to identify when performing a deltopectoral approach.

In their studies Checcia et al. and Yung et al. proposed the use of the glenoid rim as reference to localize the subscapular nerves. [6,7] Although the rim can be palpated through the subscapularis muscle during release at its anterior surface, direct visualization is not possible. This renders the intraoperative localisation of the nerves difficult.

In the present study the basis of the coracoid process was used as a reference to localize the subscapular nerve branches. As the release of the coracohumeral ligament is required when the subscapularis tendon is mobilized, the lateral border of the base of the coracoid can be seen easily.

The influence of the position of the arm has been shown to influence the relative localisation of the subscapular nerves. [6,7]. In general, circumferential subscapularis release is required when the tendon is torn and retracted. Thus the influence of the rotation of the arm is only of theoretical value only. During subscapularis repair, dissection of adhesions at the anterior surface of the subscapularis is usually performed after sutures have been passed through the tendon and the muscle-tendon unit is pulled laterally. Although tissue quality in fresh frozen cadavers is inferior to well vascularised and innervated muscle, the design of the present study gave a better basis to simulate the conditions in vivo.

The present data have shown that all superior nerve branches were located within a range 2.5 cm vertical distance below the base of the coracoid process. Within this vertical distance, there was a 95% probability to find upper subscapular nerve branches beyond a 2 cm distance medially (horizontal disctance) from the lateral border of the base of the coracoid process before release of the subscapularis tendon and with the arm held in neutral rotation. After circumferential release and with lateral traction on the tendon, the average distance between the superior nerve branches and the lateral border of the base is decreased significantly from 4.0 to 2.5 cm ($p<0.0001$). Accordingly there was a 95 % chance to find a nerve branche 0.5 cm medially from the lateral border of the base of the coracoid.

The middle nerve branches were located between 1.5 cm and 4.5 cm below the base of the coracoid process. Although they entered the muscle more medially than the superior branches, the probability to find a middle branch 2 cm medially from the lateral border of the coracoid process was 95% when the muscle was pulled laterally. Based on this analysis, there is a risk of nerve injury within the „safe harbor“ defined by Yung et al. [7]

Based on the present study, the risk to injure the lower subscapular nerves seems to be relatively low. One reason is that the nerve branches entered the muscle more medially (average distance 4.5 cm before and 3 cm after release) than the upper and middle nerve branches. Furthermore the inferior nerve branches were found within a distance between 3.5 cm and 6 cm, which corresponds to the lower border of the glenoid. As the axillary nerve is usually localised and protected at this level during surgery, it is unlikely to injure the lower subscapular nerve branches when releasing the anterior surface of the subscapularis.

In conclusion, their is a high risk for denervation of the upper part of the subscapularis muscle when release is performed underneath the conjoined tendon beyond the coracoid base and within a distance reaching from the base of the coracoid base to the axillary nerve. This is especially true when the subscapularis tendon is pulled laterally.

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2.2 SELECTIVE RECONSTRUCTION OF THE LOWER SUBSCAPULARIS WITH THE TERES MAJOR. ANATOMICAL BASIS FOR A NEW TENDON TRANSFER[2]

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2.2.1 INTRODUCTION

There is no optimal tendon transfer procedure for treatment of irreparable subscapularis tears. The idea to reconstruct the lower part of the subscapularis muscle with a teres major transfer is based on the following considerations. In his analysis of segmental innervation of the scapular muscles, Kato postulates that formation of the subscapularis muscle out of the cervical myotmes derives from 3 components of the muscle mass.[1] The larger portion, which is supplied by the superior and middle subscapular nerves forms the thoracal subscapularis muscle. The component supplied by the lower subscapular nerve, divides into a cranial and caudal portion. The cranial portion forms the lower or axillary subscapularis muscle, whereas the caudal portion becomes the teres major. Finally the third part of the subscapularis is formed by the mass is supplied by the axillary nerve. Most of the third part of the mass shifts on the dorsal side of the scapula and become the teres minor and the deltoideus muscles. Electromyographic analysis could confirm that the subscapularis muscle is composed by two functional units [2], the thoracal and the axillary parts. Based on the fact that the teres major and the axillary subscapularis belongs to the same functional unit and knowing that the

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[2] Submitted for publication to Surg Rad Anat

pectoralis major transfer does not reproduce the force vector of the subscapularis optimally, the teres major turns out to be an attractive alternative for subscapularis reconstruction.

The objective of this study was to evaluate the surgical anatomy of the teres major and its potential value as a transfer for reconstruction of the lower portion of the subscapularis muscle.

2.2.2 MATERIAL AND METHODS

Sixteen fresh frozen human cadaveric shoulders without pathology or previous surgical intervention were selected for dissection and thawed at room temperature. The skin was removed circumferentially and the deltopectoral interval identified. The deltoid was detached from the clavicle, the anterolateral acromion and it was partially detached from its humeral insertion to expose the proximal third of the humerus. The tendon of the pectoralis major was identified and dissected sharply from the humerus. Then the pectoralis major and pectoralis minor mucles were dissected carefully from the underlying structures to expose the infaclavicular portion of the brachial plexus. Care was taken not to injure the underlying neurovascular structures. Only the neurovascular pedicles to the pectoralis major and minor muscles were sectioned to facilitate exposure. The medial border of the conjoined tendon was dissected and the musculocutaenous nerve identified. Then the conjoined tendon was detached from the coracoid and the musculotendinous unit removed after the musculocutaneous nerve had been sectioned.

Attention was then turned to the humeral insertion of the latissimus dorsi muscle. The interval between the latissimus tendon and the teres major tendon was dissected. The width of the latissimus dorsi tendon at its insertion was measured. Furthermore the pattern of overlap between the latissimus tendon and the underlying teres major tendon was described. The latissimus dorsi tendon was detached from the humeral shaft, and sutures were passed through the tendon to retracted the muscle-tendon unit medially. After the width of the exposed teres major tendon was measured, it was sharply detached from the bone and tagged with three sutures using a modified Mason-Allen stitch.[3]

The next steps of dissection were directed to the identification of the neurovascular supply to the teres major. Whereas the muscle was pulled laterally, the dissection was carried on medially, identifying and preserving every vascular and neural structures entering the muscle. The entry point of each identified pedicle into the muscle was marked and the vascular anatomy was classified according to Mathes and Nahai.[4]. The distance between each pedicle and the lateral edge of the tendon was measured. To describe their topographic relationship within the brachial plexus, the pedicles were dissected and followed proximally.

Before the teres major was transferred to the lesser tuberosity, all adhesions between the latissimus dorsi and the teres major were released to optimize the availble excursion of the muscle. The axillary nerve was identified and marked with a loop. Using a transosseous fixation technique, the teres major was fixed to the lesser tuberosity. After the latissimus dorsi was sawed back to the humeral shaft , the arm was moved at the end range of all physiologic postions and the relationsship between the axillary nerve and the upper border of the transferred teres major was recorded.

2.2.3 RESULTS

2.2.3.1 Vascular supply

In 14 specimens the vascular supply to the teres major was based on one main pedicle (Type I according to Mathes and Nahai). In two specimens there were one main pedicle plus one minor pedicle (Type II according to Mathes and Nahai).

The main pedicle entered the muscle at its anterosuperior surface at an average distance of 68 mm ± SD 6 mm (range, from 55 mm to 80 mm) from the lateral edge of the tendon.

The main vessel to the teres major was a branch of the thoracodorsal artery in 11 shoulders. (Fig.1) In 4 specimens the vessel arose from the circumflex scapular artery and in one case the vessel was a branch of the subscapular artery. The main pedicle was more than 2 mm in diameter in all cadavers.

Considering the secondary pedicles, they were located between the main vessel and the humeral insertion of the tendon at 30mm and 50 mm respectively. One of these minor pedicles arose from the thoracodorsal artery and was less than 1mm in diameter. The other was a branch of the subscapular artery and was also less than 1 mm in diameter.

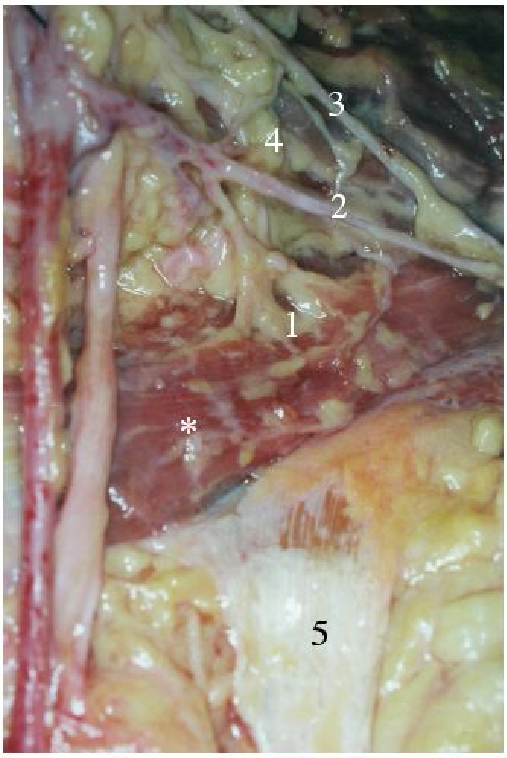


Figure 1: Anterior view of a right shoulder showing the neurovascular pedicle(1) to the teres major(*). The main artery is emerging from the thoracodorsal artery(2) and the innervation comes from the lower subscapular nerve(4). The latissimus dorsi tendon(5) has been detached from the humerus. Thoracodorsal nerve(3).

2.2.3.2 Neural supply

The nerve supply of the teres major was a branch of the lower subscapular nerve in 15 cases. In one case , innervation was coming directly from the posterior cord. The nerves entered the muscle with the main vascular pedicle in all shoulders. (Fig.1)

2.2.3.3 Description of the latissimus dorsi and teres major tendons

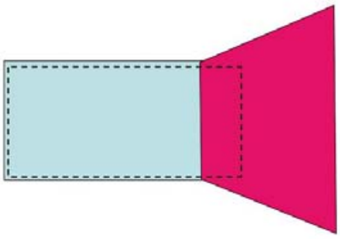
The latissimus tendon showed an average width of 34 mm ± SD 10 mm (range, from 20 mm to 52 mm). The average length of this tendon was 75 mm ± SD 11 mm (range, from 60 mm to 90 mm).

For the teres major tha average width of the tendon was 44 mm ± SD 10 mm (range, from 33 mm to 70 mm) and the average length 31 mm ± SD 7 mm (range, from 15 mm to 40 mm). Tendinous tissue was only found at the ventral surface of the muscle, whereas the posterior surface was muscular and inserting directly to the bone.

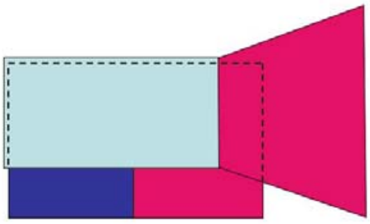
The latissimus dorsi tendon always inserted more laterally on the humeral shaft than the teres major. Between both insertions a bursa was found in all specimens, clearly separating both tendons. More medially the tendons became adherent to each other especially at their inferior edges where the latissimus muscle tendon unit is spinning around the teres major.

Furthermore the relationssship between the latissimus tendon and the teres major tendon at their humeral insertion could be divided in three patterns:

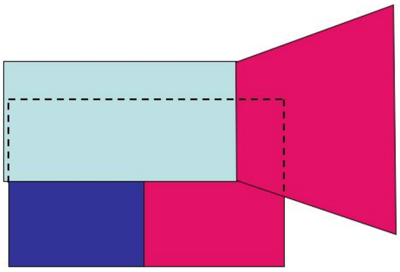
- Type I: the latissimus covers the complete teres major tendon



- Type II: the superior edge of the latissimus dorsi tendon inserts at the same level as the superior edge of the teres major, whereas the lower edge inserts more cranially.



- Type III: the superior and lower edges of the latissimus tendon insert more cranially than the superior and lower edges of the teres major.



Configuration I was found in three, configuration II in nine (Fig.2) and configuration III in four specimens.

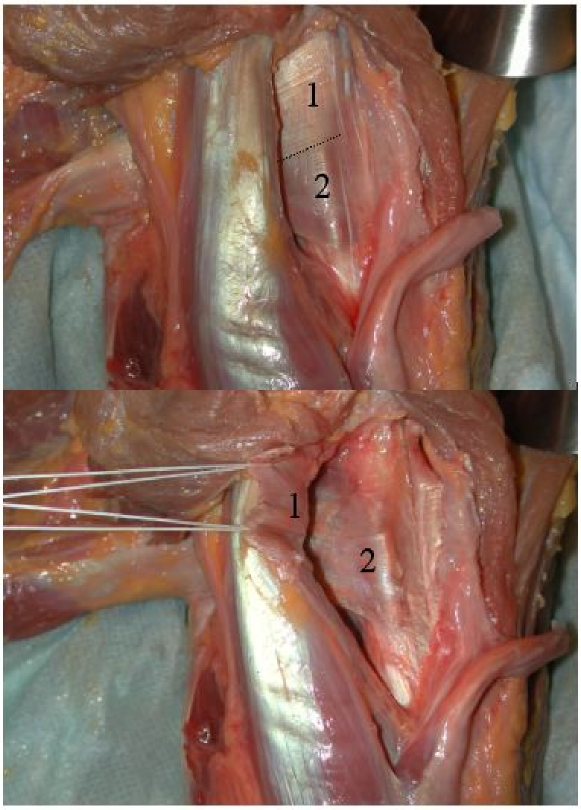


Figure 2: Type II pattern where the superior edge of the latissimus dorsi tendon(1) inserts at the same level as the superior edge of the teres major(2), whereas the lower edge inserts more cranially. The lower picture shows the complete teres major insertion(2) after detachment of the latissimus dorsi tendon(1).

2.2.3.4 Transfer of the teres major to the lesser tuberosity

The teres major muscle-tendon unit could be transferred to the lesser tuberosity easily still allowing 30° external rotation of the arm in all cadavers. However this was only possible after complete release of the adhesions between the teres major and the latissimus dorsi. Whereas the dissection plane was well defined superiorly, the muscles where adherent inferiorly. At this level, the radial nerve was approximatively 2 cm from the insertion of the lower insertion of the teres major.(Fig.3) In the transferred position and regardless of the position of the arm, there was no traction either on the vascular pedicle nor on the axillary nerve.

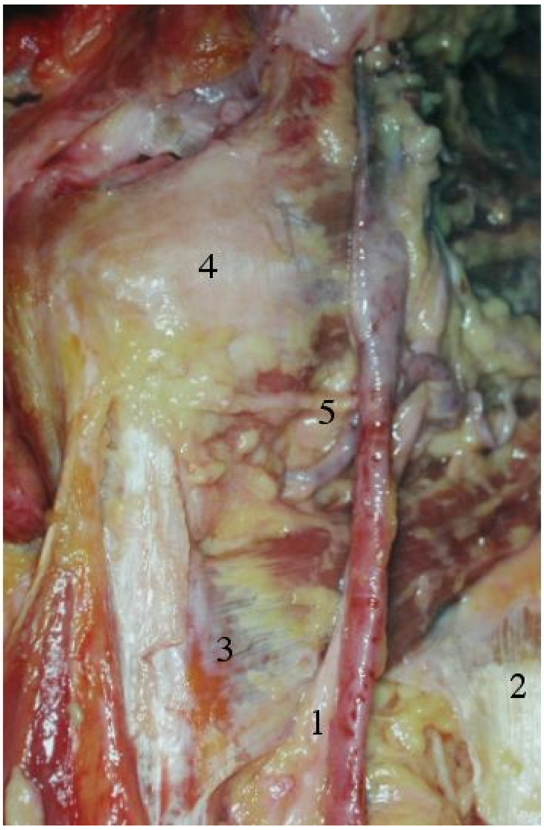


Figure 3: Note the proximity of the radial nerve(1) to the lower border of the teres major tendon(3), when the latissimus dorsi is retracted medially(2). Subscapularis(4), axillary nerve and circumflex vessels(5).

2.2.4 DISCUSSION

Several studies have analysed the anatomy of the teres major for its use as a tendon transfer for reconstruction of the posterior rotator cuff.[5-7] The descriptions are based on a dorsal approach to the shoulder. In the present study the surgical anatomy of the teres major for its use as a transfer for the subscapularis muscle was analysed and was based on a deltopectoral approach.

Furthermore in the present description, the teres major was found to be vascularized by one main pedicle located at an average distance of 7 cm from the lateral insertion of the tendon. This confirms the data published by Wang et al. .[5] However it could not be confirmed that the main pedicle of the teres major arises from the circumflex scapular artery. In the present description the artery to the teres major was a branch of the thoracodorsal artery as mentioned by Roswell et al.[8]

The innervation of the teres major by the inferior subscapular nerve was a constant finding in Kato´s and Wang´s studies[1,5] in the same way than in the present report.

As described earlier[5], and confirmed here the tendon of the teres major is relatively short and the tendinous portion of the insertion is only found at the anterior surface of the muscle. When haveresting the tendon for transfer it is essential to preserve the integrity of the tendon to allow secure repair to the lesser tuberosity. Therefore subtile dissection of the latissimus tendon is required.

The present study has shown that the latissimus dorsi most frequently covers the upper edge of the teres major tendon. This renders dissection challenging. At the lower edge there is usually a visible overlap of both tendons which facilitates their separtion. Therefore dissection in a caudocranial direction is recommended .

In all specimens it was technically possible to transfer the teres major to the lesser tuberosity. However dissection of adhesions around the muscle is required to obtain enough excursion. On the superior border of the teres major, dissection is critical due to the proximity of the axillary nerve and posterior circumflex vessels. Furthermore, preparation deeper than 5 cm medially from the lateral edge of the tendon may lead to injury of the main neurovascular pedicle of the muscle. Preparation at the inferior edge of the tendon should be performed after the radial nerve has been identified and protected with a retractor.

Although the proximalization of the tendon theoretically leads to a narrowing of the quandrangular space, this study suggests that this does not impair the axillary nerve.

On the basis of this anatomical study, the teres major seems to be a reliable and safe muscle for selective reconstruction of the axillary subscapularis.

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3 BIOMECHANICS

3.1 THREE-DIMENSIONAL ANATOMY OF THE ROTATOR CUFF

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3.1.1 INTRODUCTION

The biomechanical relevance of the rotator cuff during active motion of the shoulder joint has been studied in several experimental (in vivo or cadaveric) and analytic models. In vivo studies have included the analysis of movement after palsy or nerve block.[1] They have also estimated muscle force by electromyography[2] and and evaluate pathologic kinematics of the shoulder with radiographic studies.[3] Cadaveric studies have allowed to place known forces on the the motor units of the shoulder, while measuring the resulting movement of the joint are essentially kinematic.[4-10] The effects of structural changes like pathologies or reconstructive procedures have been predicted in analytic models based on known anatomical and geometrical properties of the shoulder joint.[11,12] Whereas the biomechanics of the normal rotator cuff has been extensively studied, they are only few information available in the literature describing the biomechanical effect of tendon transfer procedures around the shoulder.[13].

The purpose of the present study was to define an experimental model able to describe the three-dimensional anatomy of the rotator cuff.

3.1.2 MATERIAL AND METHODS

3.1.2.1 Specimen preparation

For the purpose of this study 3 fresh human torsi (2 males, 1 female) including upper extremities, trunk and pelvis were available. One specimen which had a bilateral posterior dislocation of the shoulder was excluded. Therefore 4 hemi-torsi were available for analysis. Each specimen was thawed at room temperature for 24 hours prior to testing.

For testing all specimens were fixed rigidely in the lateral decubitus. This allowed full access to the arm as well as the anterior and posterior sides of the shoulder girdle. All the skin was removed to expose the complete latissimus dorsi muscle, the pectoralis major and the serratus muscles as well as the muscles of the arm.

The deltoideus was completely resected to expose the underlying rotator cuff. Then the preparation was started with the supraspinatus muscle-tendon unit. The upper and lower edges of the muscle were identified. Dissection was carried on laterally up to the tendinous insertion side at the proximal humerus and the tendon was dissected from the underlying capsule. So the footprint of the tendon could be visualized at the greater tuberosity. The most anterolateral point of the tendon insertion was marked with a suture anchor. Using the same technique the most posterolateral point of the tendinous insertion was defined. At its muscular origine the most superomedial and inferomedial points were marked with ailet screws. Between insertion and origine 2 points along each the upper and lower edge of the muscle were marked with ailet screws. Now long braided number 2 sutures were fixed to the anterior and posterior edge of the tendon using a Bunnell stich configuration over a distance of approximatly 4 cm. At this level the muscle was cut and removed. Each pair of sutures was passed through the corresponding ailets at the lower and upper edges of the muscle. To tension the sutures and to simulating the three dimensional arrangement of the original muscle, several clamps were used.

Based on the same principle, both the infraspinatus, the teres minor, the upper and lower subscapularis, the sternal and clavuicular heads of the pectoralis major and the teres major were prepared.

After dissection the scapula was fixed rigidely to the thorax with an external fixator. The arm was fixed in neutral rotation and an image amplificator was used to ensure that the glenohumeral joint was centered.

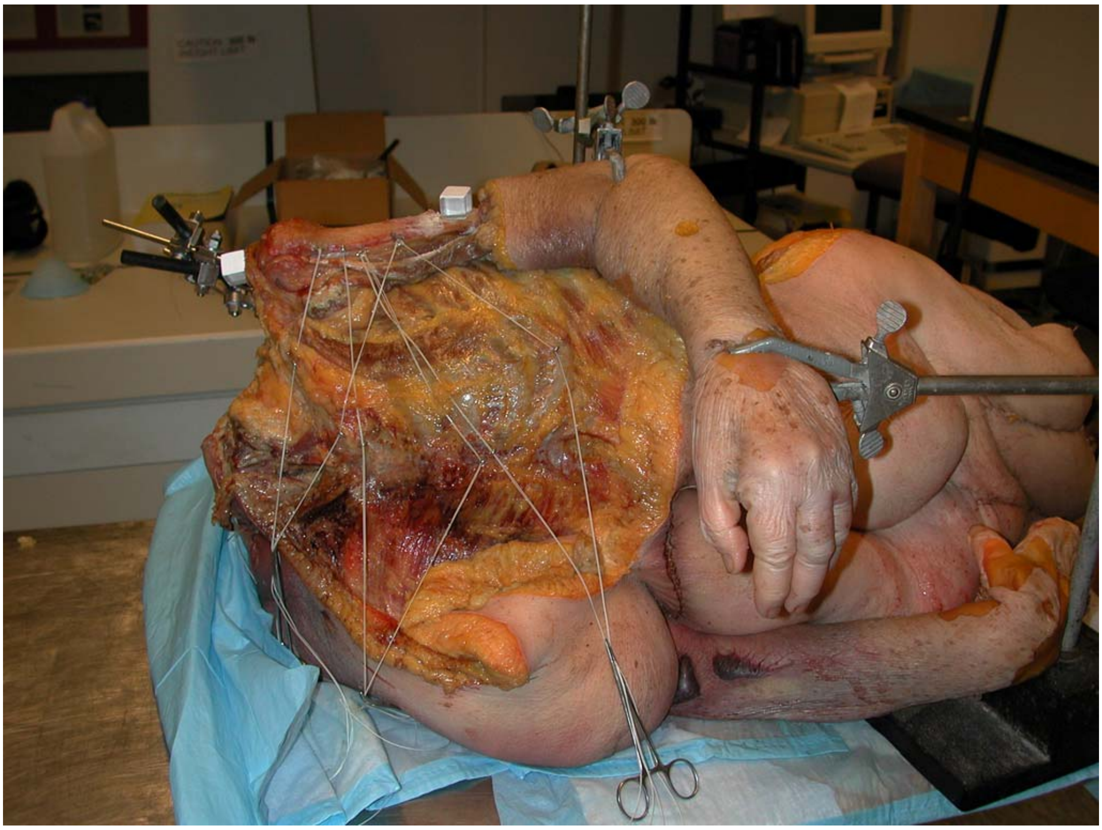

Fig 1a: Experimental set-up showing positionning of the specimen and the arm before data collection

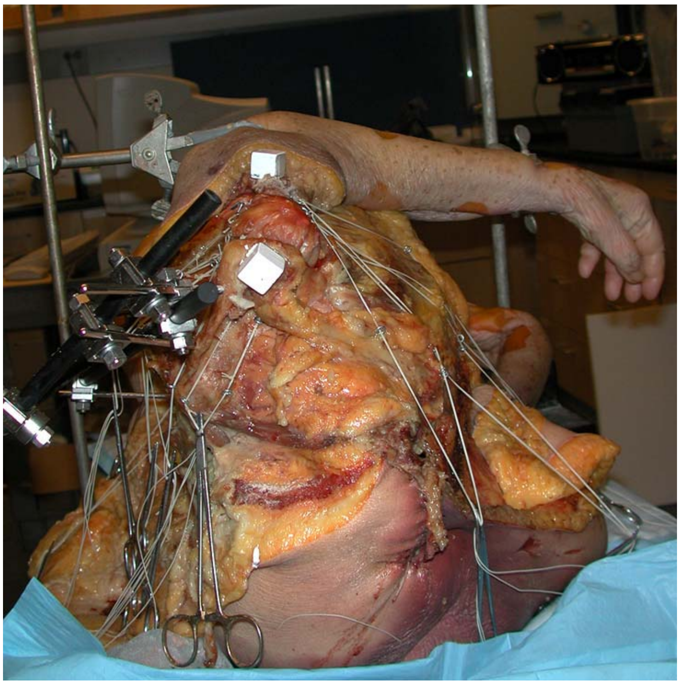

Fig1b: Superior view of th especimen. Plexiglas cubes were used to create multiple coordinate systems.

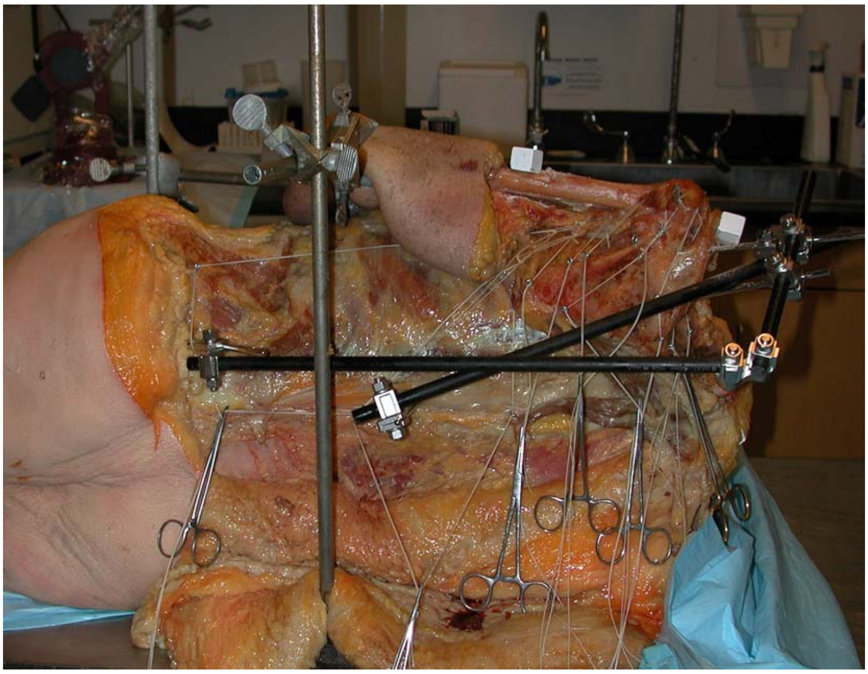

Fig 1c: The scapula was rigidly fixed to the thorax with an external fixator.

A Microscribe 3D-X digitizer (Immersion Corp., San Jose, CA) was used to register the three-dimensional anatomy of the joint and the above described muscles. The device was fixed rigidly to the custom built jig which was used to stabilize the specimens (Fig.2). Data collection was performed for four different positions of the arm:

1. Neutral Position
2. 45 degrees external rotation with the arm at the side
3. 90 degrees of abduction with 90 degrees of external rotation
4. Lift-off position with the elbow flexed at 90 degrees and the hand lying on the back at the level of L3.

The position of the scapula on the thorax was not changed when the arm was moved from one to the other position of the glenohumeral joint.

Figure 2: A Microscribe 3D-X digitizer (Immersion Corp., San Jose, CA) was used to register the three-dimensional anatomy of the joint and the above described muscles. The device was fixed rigidly to the custom built jig which was used to stabilize the specimens.

3.1.2.2 Data collection

The Microscribe 3D-X system allows measurements to be made with the manufacturer's reported accuracy of 0.23 mm. Dissections and all tasks involved in data collection were completed by the same operator (AG).

The 3D-X digitizer was used to locate the insertion points, the leading edges and the origine points of following muscle-tendon units.

(1) Supraspinatus (SS)
(2) Infraspinatus (IS)
(3) Teres minor (TMi)
(4) Lower Subscapualris (SUS(L))
(5) Upper Subscapularis (SUS(U))
(6) Complete Subscapularis (SUS(T))
(7) Teres major (TMa)
(8) Sternal head of the pectoralis major (Pec(ster))
(9) Clavicular head of the pectoralis major (Pec(clav))

After that, the shoulders were separated so that the skeletal anatomy of the humerus and the scapula could be digitized.

Multiple coordinate systems were used in this study: one to register the arrangment of the muscle-tendon units, one to register humeral anatomy, another to register scapular anatomy and a last one to combine all of the above data together. For registration of these multiple coordinate systems, small (2cm x 2cm x 2cm) registration blocks were manufactured from Plexiglas and rigidly attached to the humeral shaft and to the scapula. (Fig 1b). Three non-coplanar sides of the block were digitized at the beginning of each test and a local block coordinate system was built to serve as a cross-reference between different coordinate systems. The insertion site data, originally reported in the MicroScribe3DX™ coordinate system, were then transformed to a local block coordinate system.

3.1.2.3 Computer modelling and calculation

The collected data for each humerus were imported into Rhinoceros NURBS modeling software (McNeal and Assoc., Seattle, WA) and three-dimensional models were constructed for each shoulder. Modelling and calculation were performed by two investigators (FH, MA). Parameters describing the morphological structures were estimated from 3-D position coordinates of a large number of data points, using a least-square procedure. Tendon insertions and muscles were represented as a planes or as a (curved) line. Muscle paths were determined by a geometrical form of the bony contour around which the muscle was wrapped (Fig.3a and 3b). Hence force vectors could be calculated.

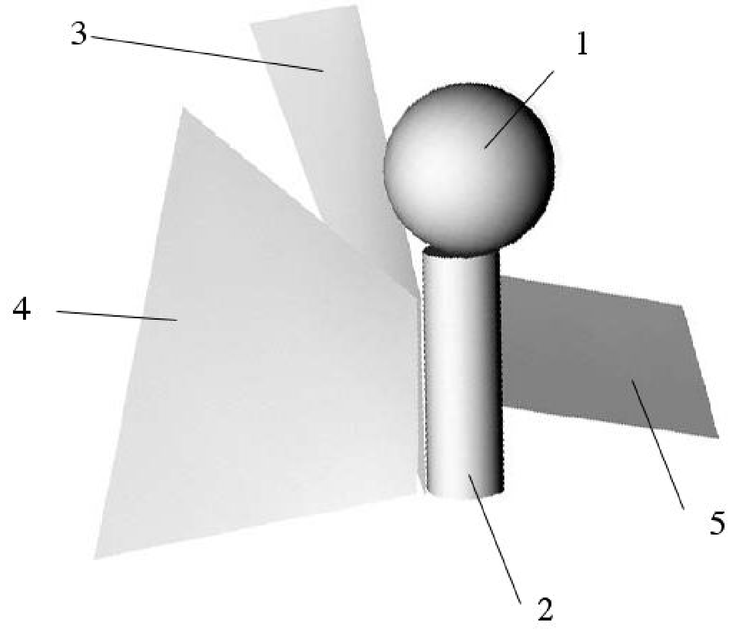

Figure 3a. Example of a model. Left shoulder from the anterior view. Humeral head(1), humeral shaft(2), clavicular head of the pectoralis major(3), sternal head of the pectoralis major(4), teres major(5).

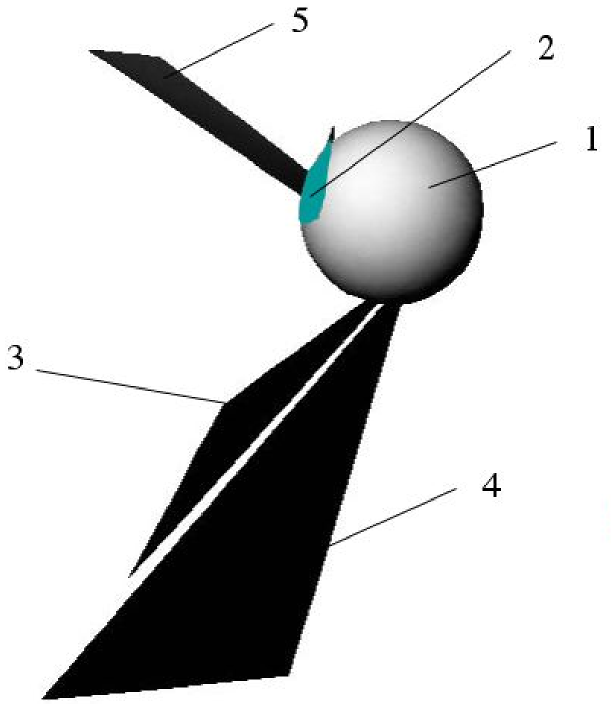

Figure 3a. Superior view. Humeral head(1), glenoid(2), clavicular head of the pectoralis major(3), sternal head of the pectoralis major(4), teres major(5).

To describe the force vector of each muscle, a transverse plane and a coronal plane perpendicular to the glenoid and to each other were used as references. α was defined as the angle between the constructed vectors and the coronal plane. The angle became negative when the vector was oriented backwards relative to the coronal plane. β was defined as the angle between the constructed vectors and the transverse plane. This angle was negative when the vector was oriented downwards relative to the transverse plane.(Fig.4)

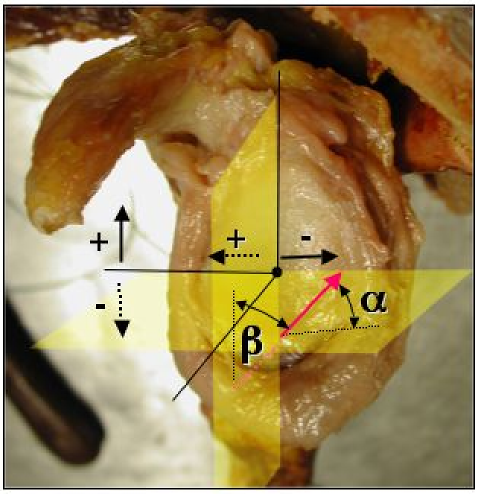

Figure 4: Definition of the reference system to calculate the angles α and β

3.1.3 RESULTS

Tables I-IV gives a overview of the vector orientation of all muscles of the rotator cuff as well as the teres major and the pectoralis major.

TABLE I: Vector orientation with the arm in position 1

		SS *(degrees)*	**IS** *(degrees)*	**SUS (U)** *(degrees)*	**SUS (L)** *(degrees)*	**SUS (T)** *(degrees)*	**Tmi** *(degrees)*	**Tma** *(degrees)*	**PEC (clav)** *(degrees)*	**PEC (ster)** *(degrees)*
SP1	β	11	11	-4	-9	-7	-15	-3	18	66
	α	2	-23	-6	-39	-23	-20	-21	60	15
SP2	β	5	13	-5	-5	-5	-13	0	7	39
	α	-1	-17	-7	-33	-22	-30	-22	57	21
SP3	β	1	8	-7	-9	-10	-18	-6	33	72
	α	3	-19	-2	-25	-16	-29	-18	49	3
SP4	β	16	20	6	3	5	-16	-1	38	72
	α	-7	-25	-22	-44	-38	-40	-36	40	12
Mean (±SD)	β	**8±6**	**13±4**	**-3±5**	**-5±5**	**-4±6**	**-16±2**	**-3±2**	**24±12**	**62±14**
	α	**-1±4**	**-21±3**	**-9±8**	**-35±7**	**-25±8**	**-30±7**	**-24±7**	**52±8**	**13±6**

TABLE II: Vector orientation with the arm in position 2

		SS *(degrees)*	**IS** *(degrees)*	**SUS (U)** *(degrees)*	**SUS (L)** *(degrees)*	**SUS (T)** *(degrees)*	**Tmi** *(degrees)*	**Tma** *(degrees)*	**PEC (clav)** *(degrees)*	**PEC (ster)** *(degrees)*
SP1	β	17	10	-2	-4	4	-6	-16	18	64
	α	-2	-17	-9	-33	-19	-21	-22	56	16
SP2	β	12	19	-1	5	12	7	-33	8	57
	α	2	-17	-2	-39	-5	-23	-14	55	29
SP3	β	5	14	-3	-11	3	-13	-14	36	69
	α	4	-21	-5	-23	-25	-13	-20	44	9
SP4	β	23	26	3	3	16	2	21	21	63
	α	-3	-22	-18	-42	-40	-34	-19	52	18
Mean (±SD)	β	**14±7**	**17±6**	**-1±2**	**-2±6**	**9±6**	**-2±7**	**-21±8**	**21±12**	**63±5**
	α	**0±3**	**-19±2**	**-8±6**	**-34±7**	**-22±13**	**-23±8**	**-19±3**	**52±4**	**18±7**

TABLE III: Vector orientation with the arm in position 3

		SS *(degrees)*	IS *(degrees)*	SUS (U) *(degrees)*	SUS (L) *(degrees)*	SUS (T) *(degrees)*	Tmi *(degrees)*	Tma *(degrees)*	PEC (clav) *(degrees)*	PEC (ster) *(degrees)*
SP1	β	7	11	-7	-6	3	-6	-10	9	50
	α	3	-14	-5	-35	-20	-23	-18	73	40
SP2	β	-1	13	-1	0	3	-3	-1	9	61
	α	8	-21	-12	-35	-25	-25	-29	63	24
SP3	β	4	-1	-14	-14	-22	-11	-19	37	73
	α	-7	-13	1	-24	-18	-17	-26	51	11
SP4	β	2	21	5	8	9	7	10	18	61
	α	-10	-28	-7	-40	-28	-28	-24	62	25
Mean (±SD)	β	**1±3**	**11±8**	**-3±7**	**-2±8**	**-3±12**	**-3±7**	**-3±11**	**22±12**	**65±8**
	α	**-3±7**	**-21±6**	**-6±4**	**-33±6**	**-24±4**	**-23±4**	**-26±4**	**59±8**	**20±10**

TABLE IV: Vector orientation with the arm in position 4

		SS *(degrees)*	IS *(degrees)*	SUS (U) *(degrees)*	SUS (L) *(degrees)*	SUS (T) *(degrees)*	Tmi *(degrees)*	Tma *(degrees)*	PEC (clav) *(degrees)*	PEC (ster) *(degrees)*
SP1	β	13	14	-6	-7	-7	5	-10	23	53
	α	2	-19	-9	-35	-28	-25	-28	13	-13
SP2	β	17	14	0	-1	1	16	-1	32	56
	α	6	-15	-12	-40	-31	-29	-33	16	-9
SP3	β	3	6	-9	-9	-12	9	-1	43	57
	α	-3	-30	-7	-24	-17	-27	-29	18	-9
SP4	β	9	27	-5	3	0	5	4	33	55
	α	-9	-38	-8	-40	-30	-54	30	15	10
Mean (±SD)	β	**11±5**	**15±8**	**-5±3**	**-3±5**	**-4±5**	**9±4**	**-2±5**	**33±7**	**55±1**
	α	**-1±6**	**-25±9**	**-9±2**	**-34±7**	**-26±6**	**-34±12**	**-15±26**	**15±2**	**-5±9**

3.1.4 DISCUSSION

The result of this study gives a set of parameters for each cadaver, describing very precisely the geometry of the selected muscles of the shoulder. The experimental model and the vector analysis for four shoulder girdles presented here create the basis for the next chapter, where vectors of tendon transfers for subscapularis reconstruction are described and compared to the vector of the original subscapularis.

Furthermore the collected data will be used in the future to develop an analytic shoulder model which eventually may help describe shoulder kinematic.

3.1.5 REFERENCES

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3.2 TENDON TRANSFER PROCEDURES FOR IRREPARABLE SUBSCAPULARIS TEARS. A THREE-DIMENSIONAL VECTOR ANALYSIS

Ariane Gerber, MD, Fraser Harrold, MD, Maria Apreleva, MD, Jon JP Warner, MD

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3.2.1 INTRODUCTION

In tendon transfer surgery the matching of force vector orientation between the transferred and the dysfunctional muscle is a difficult task. The muscles available for transfer of a given dysfunctional musculotendinous unit are limited and their anatomical arrangement is usually very different from the muscle they should replace. Furthermore the moment arm of a transferred muscle may change and become less favourable because the position of the limb is changing.

Models describing the biomechanical effects of tendon transfer procedures around the shoulder in a comprehensive way are not yet avaible.[1]

The geometrical model presented in chapter 3.1 turned out to be a suitable way to assess vector orientation of the normal rotator cuff muscles.

Based on the same methodology, it was the purpose of this study to determine the vectors of several tendon transfers commonly used for subscapularis reconstruction and to compare them with the vector of the original subscapularis.

3.2.2 MATERIAL AND METHODS

3.2.2.1 Specimen preparation

For the present study the specimens described in chapter 3.1 were used. Dissection and preparation of the muscles were performed in a same manner as described there.

The following transfers were considered:

1. PM-1: Transfer of the complete pectoralis major muscle (clavicular and sternal head) to the lesser tuberosity according to Wirth and Rockwood[2]
2. PM-2: Transfer of the complete pectoralis major (clavicular and sternal head) rerouted underneath the conjoined tendon to the lesser tuberosity according to Resch[3]
3. PM-3: Transfer of the sternal head of the pectoralis major rerouted underneath the clavicular head to the greater tuberosity according to Warner[4]
4. TM-sPM: Combined tansfer of the teres major to the lower part of the lesser tuberosity of the sternal head of the pectoralis major, rerouted underneath the clavicular head to the upper part of the lesser tuberosity.[5]

For each muscle the origine and the inserting tendon were prepared and the muscle bellies replaced by sutures as described in chapter 3.1. The three-dimensional arrangement of each unit was digitized in neutral position of the arm for all specimens.

3.2.2.2 Data collection, modelling and calculation

Using the experimental set-up described above, the transferred muscle-tendon units were digitized. The data were imported into into Rhinoceros NURBS modeling software (McNeal and Assoc., Seattle, WA) and three-dimensional models were constructed. To describe the orientation of the vector of each muscle a transverse plane and a coronal plane perpendicular to the glenoid and to each other were used as references. (Fig.1)

Again α was defined as the angle between the constructed vectors and the coronal plane. The angle was negative when the vector was oriented backwards relative to the coronal plane.

The angle β was defined as the angle between the constructed vectors and the transverse plane. This angle was negative when the vector was oriented downwards relative to the transverse plane.

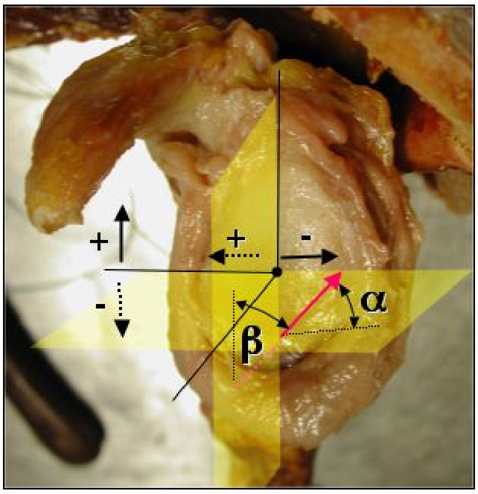

Figure 1: Two planes of reference were used to defined the vector orientation.

3.2.3 RESULTS

3.2.3.1 Pectoralis major transfer according to Wirth and Rockwood (PM-I)

Table I is showing the vectors of the complete subscapularis muscle and the pectoralis major muscle-tendon unit transferred to the lesser tuberosity.(Fig.2)

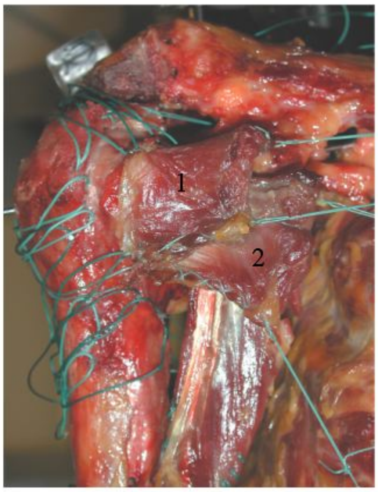

Figure 2: Anterior view of a right shoulder after PM-I tansfer. Both the clavicular (1) and the sternal head (2) have been transferred to the lesser tuberosity.

TABLE I : Comparision of the subscapularis vector and PM-I transfer vector

		SUS (Tot) *(degrees)*	**PEC (Tot)** *(degrees)*	**P Value°**
SP1	β	-7	70	
	α	-23	-10	
SP2	β	-5	73	
	α	-22	-3	
SP3	β	-10	67	
	α	-16	-14	
SP4	β	5	71	
	α	-38	-6	
Mean±SD (degrees)	β	-4±6	70.±2	< 0.0001
	α	-25±9	-8±4	0.07

°Using the Student t-test for correlated groups at a significance level of $p<0.05$

The pectoralis major transfered in a conventional way to the lesser tuberosity is oriented anteriorly relative to the coronal plane. The mean difference between the transfer and the subscapularis was approximatively 65 degrees, which was highly significant ($p<0.0001$). Relative to the transverse plane both vectors were similar.

3.2.3.2 Pectoralis major transfer by Warner (PM-II)

Table II is showing the vectors of the sternal head of the pectoralis major rerouted underneath the clavicular head and attached to the greater tuberosity.(Fig.3)

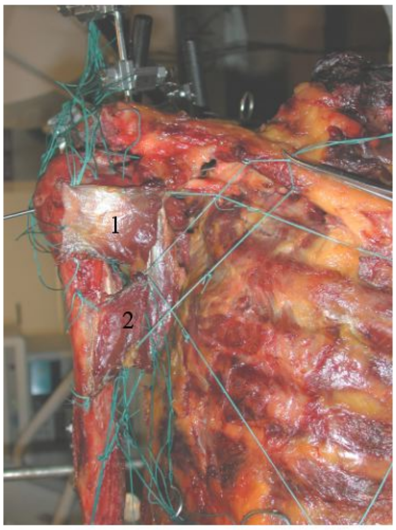

Figure 3: Anterior view of a right shoulder after PM-II tansfer. The sternal head (1) has been rerouted underneath the clavicular head and attached to the greater tuberosity.

TABLE II : Comparision of the subscapularis vector and the PM–II transfer vector

		SUS (Tot) *(degrees)*	**PEC (Ster)** *(degrees)*	**P Value°**
SP1	β	-7	66	
	α	-23	-2	
SP2	β	-5	71	
	α	-22	-6	
SP3	β	-10	52	
	α	-16	-6	
SP4	β	5	77	
	α	-38	-1	
Mean±SD (degrees)	β	-4±6	67±10	0.0002
	α	-25±9	-4±3	0.04

°Using the Student t-test for correlated groups at a significance level of $p<0.05$

Rerouting the sternal part of the pectoralis major underneath the clavicular head significantly improved the orientation of the transfer compared to the original pectoralis major transfer (p=0.04). However the vector of the transfered unit remained significantly different compared to the vector of the subscapularis relative to both planes (p=0.0002 and p=0.04).

3.2.3.3 *Pectoralis major transfer by Resch (PM-III)*

Table III is showing the vectors of the complete pectoralis major rerouted underneath the conjoined tendon and attached to the lesser tuberosity.

TABLE III: Comparision of the subscapularis vector and the PM-III vector

		SUS (Tot) *(degrees)*	**PEC (Tot)** *(degrees)*	**P Value°**
SP1	β	-7	40	
	α	-23	-7	
SP2	β	-5	44	
	α	-22	-9	
SP3	β	-10	34	
	α	-16	-12	
SP4	β	5	63	
	α	-38	-3	
Mean±SD (degrees)	β	-4±6	45±13	0.0005
	α	-25±9	-8±4	0.078

°Using the Student t-test for correlated groups at a significance level of $p<0.05$

The data showed that with this transfer the vector relative to the coronal plane could be improved from an average of 70 degrees (conventional transfer) to 45 degrees(rerouted transfer). This difference was statistically significant (p=0.02). However comparision between the subscapularis vector and the vector of the transfer still remained different (p=0.0005)

3.2.3.4 *Combined teres major-split pectoralis major transfer (TM-sPM transfer)*

Table IV is showing the vector of the teres major transfer and comparing it with the vector of the lower subscapularis. The table shows also the comparision between the vector of the rerouted sternal head of the pectoralis major after transfer to the lesser tuberosity and the vector of the upper subscapularis.(Fig.4)

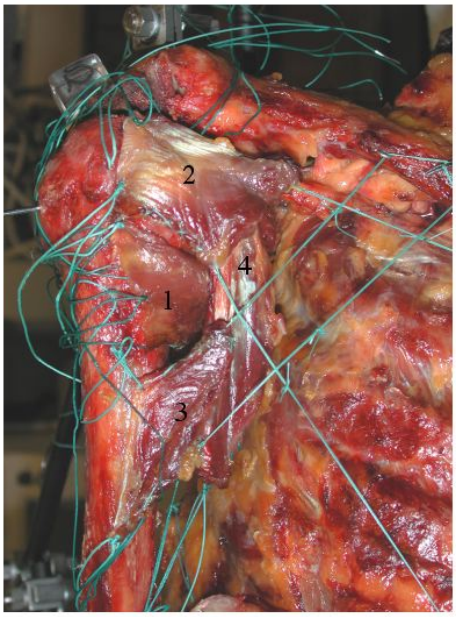

Figure 4: Anterior view of a right shoulder after TM-PM tansfer. The teres major(1) has been transferred to the lower part of the lesser tuberosity, whereas the sternal head of the pectoralis major(2) has been rerouted underneath its clavicular head(3) and attached to the superior part of the lesser tuberosity. Conjoined tendon (4)

TABLE IV : Comparision of the subscapualris vectors and the TM-PM transfer vectors

		SUS(L) *(degrees)*	**TMa** *(degrees)*	**P Value°**	**SUS(U)** *(degrees)*	**PM(Ste)** *(degrees)*	**P Value°**
SP1	β	-9	-7		-4	68	
	α	-39	-34		-6	-22	
SP2	β	-5	-9		-5	66	
	α	-33	-42		-7	-13	
SP3	β	-9.45	-17		-7	63	
	α	-25	-38		-2	26	
SP4	β	3	-13		6	76	
	α	-44	-54		-22	0	
Mean±SD (degrees)	β	-5±6	-12±5	0.17	-2±6	68±5	<0.0001
	α	-35±8	-42±9	0.21	-9±9	-15±12	0.59

°Using the Student t-test for paired groups with a significance level set at p<0.05

In this model we could not find a difference between the vector orientation of the teres major and the lower part of the subscapularis (p=0.17, p=0.21). Comparing the reconstruction of the upper subscapularis with split pectoralis major, the difference of the vector orientation was significant relative to the coronal plane ($p<0.0001$). Relative to the transverse plane the vector orientation of the upper subscapularis and the split pectoralis major were similar ($p=0.59$).

3.2.4 DISCUSSION

The present study is the first description of the three dimensional geometry of tendon transfer procedures around the shoulder. In their study Magermans et al. used the finite element model described by van der Helm to anlayze different configurations of the latissimus dorsi and the teres major transfers for reconstruction of the posterior rotator cuff [6] In their analysis the authors did not assess geometry of the tendon transfers experimentally.

With this experimental model it was possible to quantitatively describe the influence of rerouting procedures when performing a pectoralis major transfer. The most effective way to change the anterior orientation of the pectoralis major vector was to reroute it underneath the conjoined tendon. However none of the proposed techniques was able to restore the vector of the subscapularis relative to the coronal plane.

The data furthermore demonstrated that the pectoralis major transfers and the subscapularis have a similar orientation relative to the transverse plane. As the subscapularis is, the pectoralis major transfers described in this work all were oriented downwards.

In chapter 2.2 it was demonstrated, that anatomically speaking the teres major is a valuable transfer for reconstruction of the lower subscapularis. With the present analysis it could be shown that this muscle exactly replicates the three-dimensional geometry of the axillary subscapularis.

A weakness of the present analysis is the small number of specimens. To create an analytic model based on these data further measurements will be required.

3.2.5 REFERENCES

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4 CLINICAL APPLICATIONS

4.1 THE COMBINED TERES MAJOR AND SPILT PECTORALIS MAJOR TRANSFER FOR SELECTIVE RECONSTRUCTION OF IRREPARABLE SUBSCAPULARIS TEARS[3]

A preliminary report

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4.1.1 INTRODUCTION

Loss of subscapularis function leads almost invariably to painful dysfunction of the shoulder. Whereas excellent results with restoration of mobility and strength can be expected after direct repair of the tendon in reparable subscapularis tears [1], the outcome after surgical treatment of chronic lesions is less predictable. For chronic irreparable ruptures reconstruction tendon transfer has been recomended. None of the the proposed tendon transfers, like the trapezius transfer, the pectoralis major or the pectoralis minor transfer are able to restore the vector of the subscapularis muscle which may partly explain the variable clinical success of such procedures. [2-8]

The aim of this study was to define a new surgical concept for irreparable subscapularis tears basing on the selective reconstruction of the subscapularis muscle-tendon unit with a combined teres major and split pectoralis major tendon transfer. In addition a report of the early clinical experience is presented.

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[3] Submitted to J. Shoulder Elbow Surg.

4.1.2 MATERIAL AND METHODS

4.1.2.1 Concept of selective subscapularis reconstruction (Fig.1)

The anatomical and biomechanical data presented above were used to design a new reconstruction procedure for irreparable subscapularis tears. The cadaveric dissection showed that it is technically possible and safe to transfer the teres major to the lower part of the lesser tuberosity. Furthermore the orientation of the force vectors of the transferred teres major and of the lower subscapularis were similar. Thus the teres major transfer is a logical choice for reconstruction of the axillary part of the subscapularis.

The reconstruction of the superior part of the subscapularis remains an unsolved problem. The vector analysis presented above suggests that the orientation of the pectoralis major transfer is similar to the subscapularis relative to the transverse plane. However the force vector orientation relative to the coronal plane remains profoundly different from that of the subscapularis, even after modification of the transfer, like the subcoracoid transfer by Resch[8] or the split pectoralis major transfer by Warner.[7]

The patients involved in this study, all had had multiple procedures performed on their shoulder. Thus, extensive scarring of the anterior structures of the glenohumeral joint was expected. Therefore the split pectoralis major transfer by Warner was chosen for reconstruction of the upper subscapularis muscle to avoid injury to the musculocutaneous nerve.

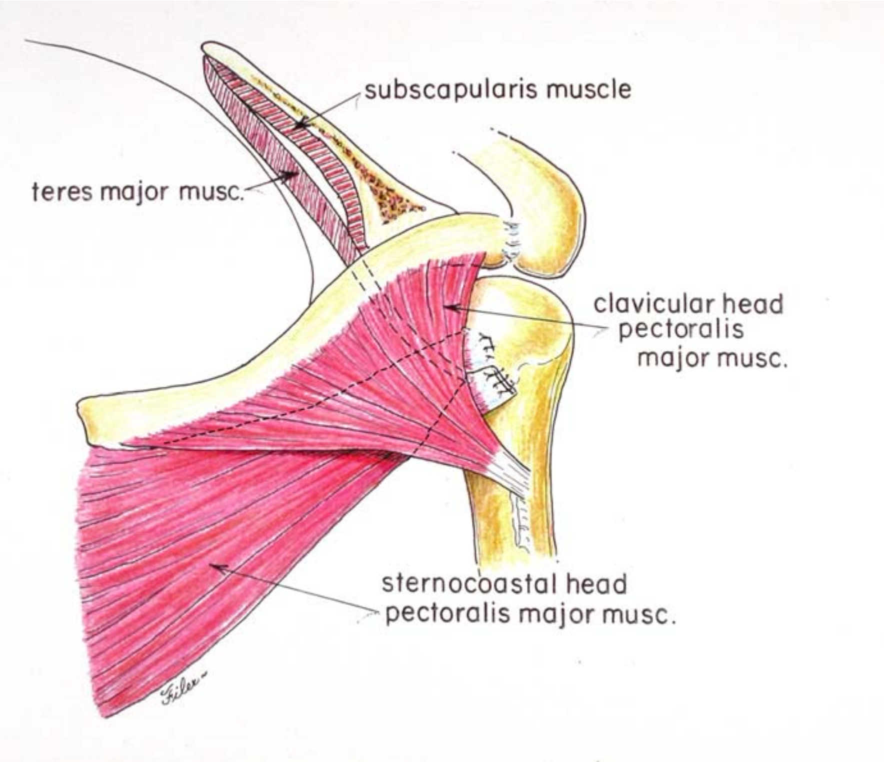

Figure 1: Schematic representation of the transfer illustrating the principle of selective reconstruction of the subscapularis muscle. The teres major muscle is transferred to the lower lesser tuberosity whereas the sternal part of the pectoralis major is rerouted underneath its clavicular head and fixed to the upper tuberosity.

4.1.2.2 Patients

Seven patients with a complete irreparable tear of the subscapularis were treated with a combined teres major-split pectoralis major transfer (combined TM-sPM transfer) by the author of this monography. There were 2 females and 5 males with an average age of 45 years (ranging from 34 to 65 years) at surgery.

All patients had had surgery involving the subscapularis tendon (1-6 procedures) prior the index procedure.(Table I)

TABLE I : **Demographic data and history of first seven patients treated with a combined TM-sPM transfer**

Case	Age at surgery	Primary Pathology	Number and Type of previous procedures prior index surgery
1	66	Instability	(1) Putti-Pate procedure (2) open subacromial decompression; (3) Total shoulder replacement
2	42	Instability	(1) Arthroscopic Bankart repair; (2) Open capsular shift
3	45	Fracture of the greater tuberosity	(1) ORIF greater tuberosity; (2) Open capsular release
4	42	Instability	(1)AC joint resection; (2)Debridement and irrigation for infection; (3)Open capsular shift; (4)Biceps tenodesis; (5) Open subacromial decompression; (6) Debridement and irrigation for infection
5	47	Rototor cuff tear	(1)Rotator cuff repair
6	34	Instability	(1) Open subacromial decompression; (2) Biceps tenodesis; (3)Iopen capsular shift
7	40	Instability	(1)Shoulder arthroscopy; (2) open Bankart repair; (3) Shoulder arthroscopy; (4) open capsular repair

4.1.2.3 Structural lesions, indication for transfer surgery (Table II)

MRI or CT-scan was available for each patient before surgery. Two patients had an isolated irreparable subscapularis tear. In one patient there was a combined reparable supraspinatus and irreparable subscapularis tear. In the other patients both the supraspinatus and infraspinatus were deemed to be irreparable. In all but one patients the glenohumeral joint was normal without degenerative changes. One patient already had sustained total shoulder replacement arthroplasty. This and another patient two showed static anterior subluxation on the preoperative axillary view.

Although the subscapularis muscle was deemed to be irreparable based on the preoperative imaging in all shoulders, final decision for tendon transfer was taken during surgery.

TABLE II : Structural lesions

Case	Glenohumeral joint	Tear configuration°
1	Replaced, anteriorly subluxed	irreparable anterosuperior tear
2	No degenerative signs, centered	combined reparable supraspinatus tear, irreparable subscapularis tear
3	No degenerative signs, anteriorly subluxed	irreparable anterosuperior tear
4	No degenerative signs, centered	irreparable subscapularis tear
5	No degenerative signs, centered	irreparable anterosuperior tear
6	No degenerative signs, centered	irreparable subscapularis tear
7	No dgenerative signs, centered	Irreparable subscapularis tear

°The tear was considered irreparable if fatty degeneration > than grade II (according to Goutallier et al. on CT-scan (Goutallier, 1994 #1221), according to Fuchs et al. on MRI[9])

4.1.2.4 Surgical technique

Surgery was performed under a combined locoregional and general anesthesia allowing for optimal pain management and relaxation after extubation. The procedure was performed in the beach-chair position through an extended deltopectoral approach to facilitate exposure of the inferior border of the sternal part of the pectoralis major and the humeral insertion of the latissimus dorsi. First, all adhesions between the humeral head and the deltoid were released. The interval between the conjoined tendon and the pectoralis major was developed. In all cases the subcapularis tendon was retracted medially, deep underneath the conjoined tendon. The scar tissue covering the lesser tuberosity was removed and a humeral head retractor was used to displace the humeral head posteriorly and facilitate dissection. The tendon of the long head of the biceps, if still intact was invariably medially dislocated and degenerated. In these cases it was tenotomized and tenodesed to the short head of the biceps. With the humeral head pushed posteriorly the retracted tendon of the subscapularis could be identified. Braided number-2 sutures were passed through the edge of the subscapularis tendon. The anterior circumflex vessels and the axillary nerve were identified. The vessels were controlled with suture ligature and a vessel loop was placed around the nerve. To protect the axillary nerve, a Blunt Hohman retractor was placed between the nerve and the underlying scarred subscapularis muscle. The subscapularis muscle-tendon unit was released circumferentially. In all patients, the complete subscapularis was considered irreparable. Therefore no attempt was made to refix the degenerated muscle to the proximal humerus.

The detailled surgical technique has already been published by the author of this monography and designer of the transfer.[10] The relevant steps of the procedure are decribed in Figures 2 to 8.

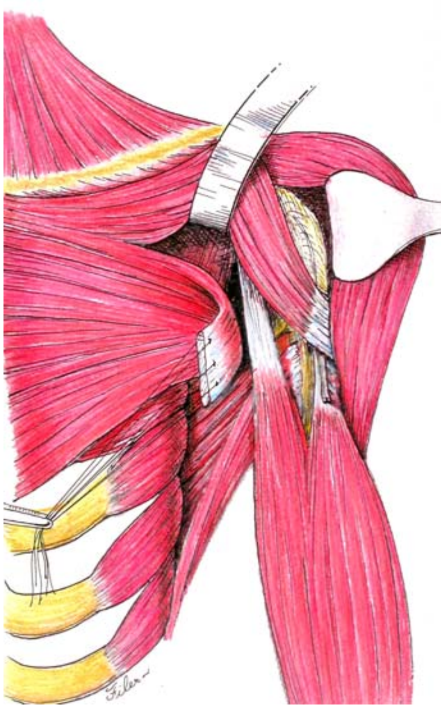

Figure 2: The pectoralis major tendon is identified at its humeral insertion. The tendon of the sternal head, which inserts to the humerus underneath the clavicular head, is carefully dissected and sharply released from the bone humerus. Number 2, braided, nonabsorbable sutures are placed through the end of the pectoralis tendon using modified Mason-Allen stiches. The sternal head of the pectoralis major muscle is dissected medially so that it can be oriented laterally and cranially. Medial dissection should not exceed 10 cm to avoid denervation of the sternal head[11].

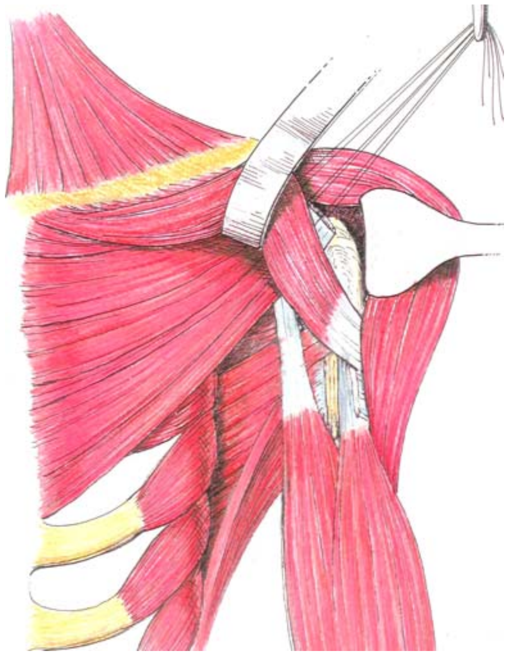

Figure 3: After dissection the sternal head is rerouted underneath the clavicular portion of the muscle.

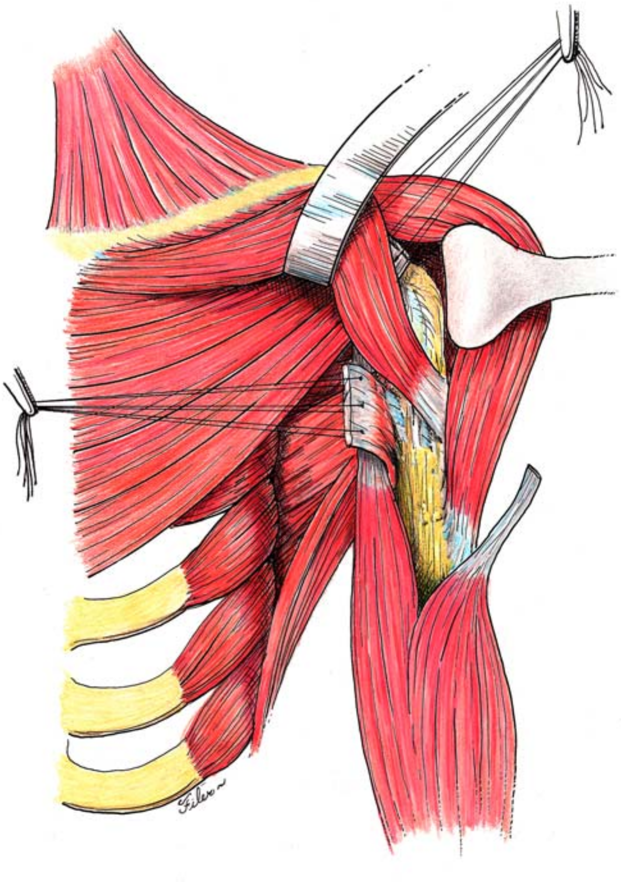

Figure 4: With the arm in maximal external rotation, the tendon of the latissimus dorsi ist exposed. The upper and the lower border are dissected before the tendon is released from the humerus.To allow refixation of the latissimus tendon at the end of the procedure, a 1 cm large cuff of tendon is left at the humeral shaft. The release tendon is reflected medially after 3 pairs of number 2 braided non-absorbable sutures have been placed in the tendon.

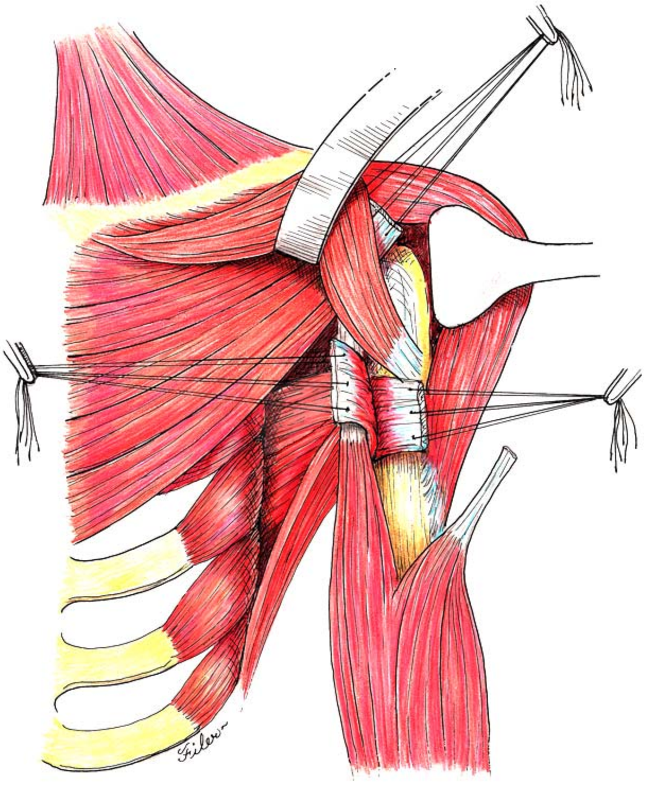

Figure 5: The plane between the latissimus dorsi and the teres major tendons is well defined laterally, closed to their humeral insertion. Medially the plane becomes less clear and dissection must be meticulous to avoid any damage to the short tendon of the teres major muscle. After exposure of the upper and lower border of the teres major muscle, the tendon is elevated subperiosteally from the humeral shaft and three sets of number 2 braided non-absorbable sutures are placed through the tendon in a modified Mason-Allen configuration.

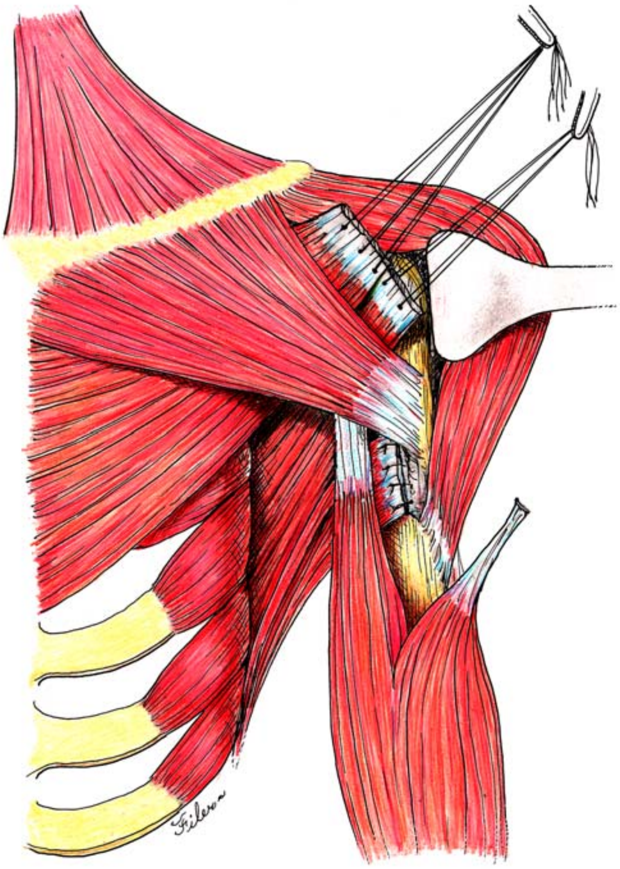

Figure 6: The teres major tendon is then mobilized by releasing adhesions to the latissimus dorsi. Dissection at the upper border of the teres major should be performed carefully to avoid any damage to the axillary nerve and the posterior circumflex vessels. Furthermore medial dissection between latissimus dorsi and teres major should not exceed 5 cm from the humeral end of the teres major tendon to save the main pedicle of the transfer. Usually adhesions limiting cranial mobilisation are found between the lower edge of the teres major and the latissimus dorsi and must be released. Before doing so, the surgeon should be aware of the exact location of the radial nerve and the deep brachial artery. Finally the tendon is transferred to the lower portion of the lesser tuberosity. The latissimus is repaired to the humeral shaft.

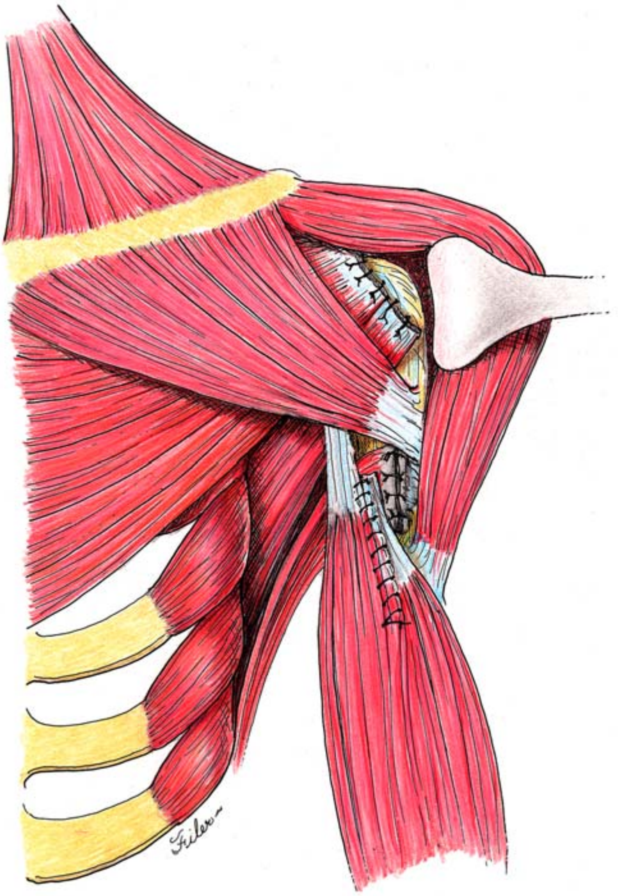

Figure 7: The lesser tuberosity and the bicipital groove are decorticated. Both transferred tendons are fixed to the lesser tuberosity using transosseous sutures. The teres major is fixed first to the lower part of the lesser tuberosity. As a rule the transfer should already be tight in neutral rotation, but still allowing 20°-30° of passive external rotation.Then the sternal head of the pectoralis major is fixed to the upper part of the lesser tuberosity with the arm held in 30° of external rotation. The rotator interval between the leading edges of the supraspinatus and the split pectoralis major transfer is closed.

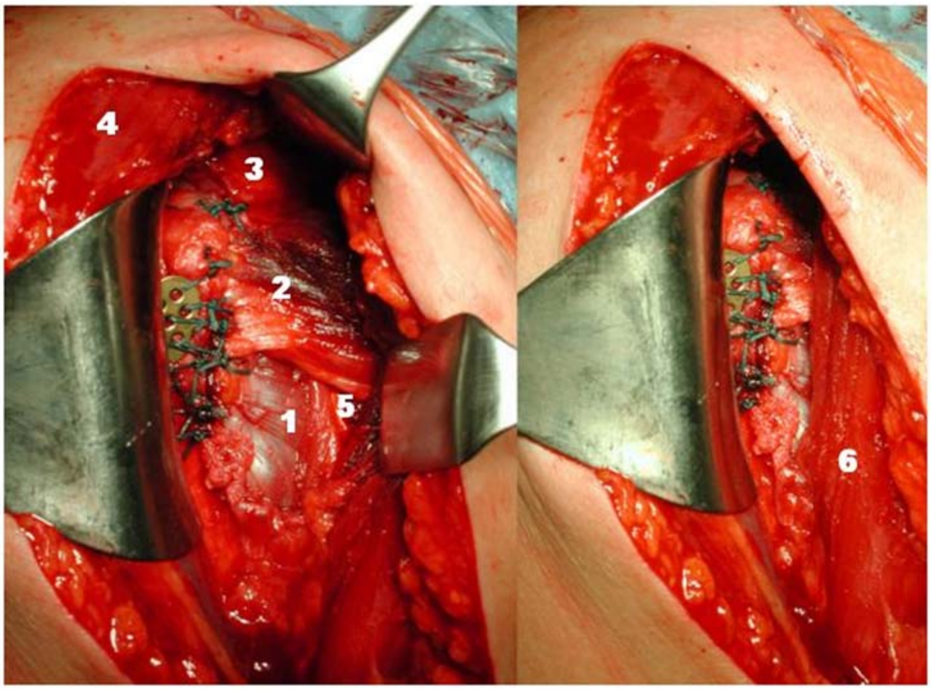

Figure 8: Intraoperative view of a right shoulder after completion of the combined teres major and split major transfer. Teres major(1), sternal part of the pectoralis major(2), supraspinatus tendon(3), deltoideus(4), conjoined tendon(5), clavicular part of the pectoralis major(6).

All patients were immobilized in a sling for 6 weeks. Passive range of motion was performed through a physical therapist 3 times a week during this time. After 6 weeks the sling was removed and active-assisted motion was started. Unrestricted active range of motion was allowed 8 weeks after surgery and strengthening 4 months postoperatively.

4.1.2.5 Evaluation

The preoperative and postoperative clinical evaluation was performed with the Constant score.[12] The score is assigning 0-35 points for subjective assessment (0-15 points for pain and 0-20 points for ability to perform daily activities) and a maximum of 65 points for the objective assessment of the shoulder (0-40 points for mobility, 0-25 points for strength).

Furthermore patients were ask to rate their satisfaction in four categories (very satisfied, satisfied, unsatisfied, disappointed).

Before surgery and at the follow-up visit an anteroposterior and a axillary view of the operated shoulder were taken in all patients. The axillary view was used to measure subluxation of the humeral head. Subluxation was defined as a shift of the center of the humeral head relative to the mid-distance of the glenoid.

To compare the postoperative outcome measures with the preoporative evaluation, the Wilcoxon test for correlated groups was used. The level of significance was set at $p<0.05$.

4.1.3 RESULTS

4.1.3.1 Clinical outcome (Table III)

At a minimum follow-up period of 12 months (range, 12 to 18 months) all patients were evaluated clinically and radiographically.

In the complete series (N = 7) the average relative Constant score increased from an 7% (range, 1 to 38) percent preoperatively to 40% (range, 4 to 76) at follow-up ($p=0.0277$). The average number of points assigned for pain evaluation increased from an average of 0 points (range, from 0 to 5) to 8 points(range, from 5 to15) after transfer ($p=0.018$). The average flexion was only 70 degrees (range, from 30 to 130) before surgery and was 90 degrees (range, from 60 to 170) at follow-up ($p=0.0277$).

The clinical subscapularis signs remained positive in all shoulders. However apprehension in adduction disappeared in 6 from 7 patients.

Patient satisfaction was high (3 patients very satisfied, 3 patient satisfied). One patient who had to be reoperated was disappointedThe sastisfied patients stated that they would recommend the procedure to another patient having a same problem they had.

TABLE III: Relevant preoperative and postoperative clinical data

Case	**Relative Constant score** *(%)*°		**Pain** *(points)*		**Active forward flexion***(degrees)*		**Apprehension**	
	Preop	**Postop**	**Preop**	**Postop**	**Preop**	**Postop**	**Preop**	**Postop**
1	1	49	0	10	50	90	pos	neg
2	20	25	0	6	70	70	pos	neg
3	7	37	0	15	40	90	pos	neg
4	4	4	0	0	30	60	pos	pos
5	7	80	5	12	90	170	pos	neg
6	38	47	5	8	130	140	pos	neg
7	30	40	0	8	100	150	pos	neg

° In this series no patient was able to perform resisted painfree abduction before and after surgery. Based on the original descritpion of the score, 0 point was attributed for strength in all patients before surgery and at followup.

4.1.3.2 Radiographic outcome

No increase of asteoarthritic changes could be seen between the preoperative and postoperative evaluation. On the axillary view the humeral head was subluxed anteriorly in 2 patient s before surgery. At follow-up all humeral heads appeared centered on the axillary view. (Fig.9b)

4.1.3.3 Complications

In all cases the procedure was carried out without complications. There were no early infections or neurologic complications.

One patient had a deep late infection and fusion was performed 1 year after the tendon transfer procedure. At the time of surgery both components of the transfer were found to be insufficient. This patient had alreadybeen operated 6 times before tendon transfer.

4.1.4 DISCUSSION

Restoring muscle balance of the shoulder with tendon transfer to treat irreparable subscapularis or anterosuperior tears is one of the most challenging task in the surgery of the shoulder.

In Europe there is a trend towards treatment of irreparable rotator cuff tears with the implantation of a reversed replacement arthroplasty in the eldery patient. This is usually not an acceptable solution for the younger individual because longterm results with the inverse prosthesis are not known.

Based on anatomical and biomechanical considerations, a new concept of subscapularis reconstruction was defined. Theoretically, it appears that the teres major may improve the performance of the pectoralis major transfer.

No complications related to the transfer occured in this series, confirming that the transfer of the teres major from the humeral shaft to the lesser tuberosity through a deltopectoral approach is a reliable and safe procedure.

In this series, six from seven patients were younger than 50 years and had a normal cartilage of their glenohumeral joint. The preoperative clinical situation was desperate charaterized by intolerable pain and loss of function after multiple surgeries. Therefore the transfer procedure was considered as a salvage procedure in this series. Nevertheless the early clinical results with the TM-sPM transfer were encouraging. Early pain relief occured in all case and all patients (including the one who had to be reoperated) considered pain relief as the main gain after surgery, although none of them was completely painfree.

Although flexion increased significantly after surgery, the overall functional gain remained modest and the clinical subscapularis tests remained positive. However apprehension in external rotation with the arm at the side disappeared in six from seven cases and facilitated activity of daily living (Fig 9a).

Figure 9a: Clinical outcome (18 months postoperatively) of 65 years old women treated for irreparable anterosuperior tear after total shoulder arthroplasty with total shoulder revision and TM-sPM transfer. Before surgery she had a painful pseudoparalysis of the right arm.

Due to its orientation and position at the calcar of the proximal humerus, the teres major may play role as stabilizator of the joint sustaining the humeral head like hammock and pulling it backwards (Fig.9b). Investigation of muscle activity with electromyography will be required to evaluate the function of the teres major transfer as a joint stabilizer.

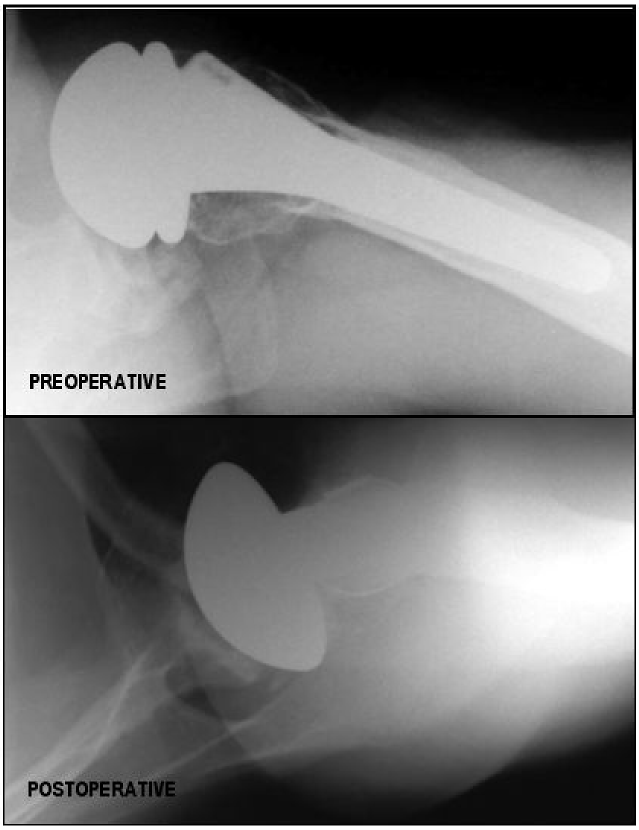

Figure 9 b: The preoperative axillary view of the shoulder of patient of Figure 9a shows a clear anterior subluxation of the prosthetic head (upper picture). After revision of the prosthesis and TM-sPM transfer the shoulder is centered (lower picture).

The comparision of these results with other studies is difficult. The patient population considered here is highly inhomogenous . Furthermore 5 from 7 patients had combined anterosuperior tears. Finally all patients had had multiple surgeries before the index procedure.

Although the series presented is very small, the combined TM-sPM transfer appears to be a valuable and a safe alternative to treat irreparable subscapularis tears. The early promising subjective and objective results presented here encourage for further investigation.

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5 CONCLUSIONS

As a primary pathology of the rotator cuff irreparable suscapularis ruptures are rare. However insufficiency of this muscle-tendon unit has been described as one of the most frequent complications after total shoulder arthroplasty or open instability surgery[1-3] and the incidence of chronic irreparable lesions is increasing.

In revision surgery there is a potential risk for denervation of the muscle. In the first chapter, it could be demonstrated that the superior and middle subscapular nerves are at risk when extensive release is required at the anterior surface of the muscle. This was especially true when the subscapularis tendon was pulled laterally. In this situation the „safe harbor“ turns out to be the lateral border of the base of coracoid process.

If a chronic subscapularis tear requires surgical treatment , reconstruction with a tendon transfer has been proposed. Unfortunatly there is no optimal transfer for the subscapularis muscle. In chapters 2.2, 3.1 and 3.2 the anatomical and biomechanical basis for a new concept of selective subscapularis reconstruction have been established. Based on these studies it could be demonstrated that the teres major is a safe and biomechanically logical transfer for reconstruction of the lower part of the subscapularis. The analysis was carried on to define the optimal transfer for reconstruction of the upper part of the subscapularis. In Chapter 3.2 it was possible to determine the biomechanical effect of rerouting procedures of the pectoralis major transfer. Passing the tendon underneath the conjoined tendon seems to be the most effective way to improve the direction of the pectoralis major transfer for subscapularis reconstruction. However this technique is demanding when the plane underneath the conjoined tendon is scarred and the pectoralis major is bulky . In such cases there is a risk to injure the musculocutaneous nerve.[4] Therefore, the split pectoralis major tendon may be a safer option.

Although the clinical series presented in chapter 4.1 is small, the combined TM-sPM transfer appears to be a valuable and a safe alternative to treat irreparable subscapularis tears. An interesting observation in this study was that the transfer was able to recenter the statically subluxed humeral head in two cases. This could be attributed to the dynamic hammock built by the transferred teres major. The early promising subjective and objective results presented here encourage for further investigation.

For the sake of completeness it should be emphasized that together with improvement of surgical technique, careful patient selection and scrupulous postoperative rehabilition are essential to achieve an optimal clinical outcome. Furthermore, the subscapularis insufficiency is a unequivocal clinical entity which should be diagnosed early to allow primary repair.

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