Compensatory muscle activation in patients with glenohumeral cuff tears

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Chapter 5

Teres major muscle activation relates to clinical outcome in tendon transfer surgery

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Abstract

In irreparable rotator cuff tears a teres major tendon transfer to the insertion of the supraspinatus reverses its *ad*duction moment arm to *ab*duction which is supposed to be an adequate salvage procedure. Analysis of muscle function to find biomechanical ground of such success is scarce.

We compared pre- and postoperative clinical outcome of a teres major transfer, i.e. Range of Motion, pain, Constant Shoulder scores and arm force. Teres major activation was evaluated in fourteen patients suffering irreparable cuff tears using *activation ratios* to describe the desired 'in-phase' and undesired 'out-of-phase' contribution to the external arm moment. Additionally, we analyzed activation of the latissimus dorsi and the medial part of the deltoids. The *activation ratios* were compared to controls and teres major *activation ratios* were related to clinical outcome.

A teres major tendon transfer improved arm function. Preoperatively, we observed 'out-of-phase' *ab*duction activation of the teres major and latissimus dorsi. After transfer patients activated their teres major according to its new anatomical position. 'Out-of-phase' latissimus dorsi *ab*duction activation persisted. The clinical improvements coincided with changes in *activation ratio* of the teres major.

'Out-of-phase' teres major *ad*ductor activation is associated with compromised arm function in patients with irreparable cuff tears. After transfer, the teres major is activated in correspondence with its new anatomical function, which was supportive for the improved arm function.

5.1 Introduction

Patients with irreparable rotator cuff tears are restricted in their daily activities due to limitations in arm Range of Motion (*RoM*) and pain (Iannotti et al., 1996; Jost et al., 2000). Conservative treatment often evolves into progressive cuff degeneration, proximal migration of the humeral head or sweeping cuff tear arthropathy (Hawkinds and Dunlop, 1995; Levy et al., 2008; Zingg et al., 2007). Restoration of the torn and degenerated cuff muscle(s) frequently results in re-tears and unsatisfying functional improvements (Birmingham and Neviaser, 2008; Elhassan et al., 2008). Alternatively, muscle-tendon transfers have been proposed as a salvage procedure to restore arm function with moderate to good results (Aoki et al, 1996; Boileau et al., 2007; Celli et al., 2005; Celli et al., 1998; Codsi et al., 2007; Gerber et al., 1988; Gerber et al., 2000; Iannotti et al., 2006; Irlenbusch et al., 2008b; Miniaci and MacLeod, 1999; Warner and Parsons, 2001).

High quality randomized controlled blinded clinical trials, investigating the effect of tendon transfers are not feasible. The available clinical studies are generally descriptive, preferably using large cohorts, because of individual variation in functional outcome (Gerber et al., 2006). The alternative is to find determinants of functional outcome after tendon transfer surgery, for which biomechanical modeling and experimental testing is required. Biomechanical model simulations (Magermans et al., 2004a; Magermans et al., 2004b) and anatomical studies (Wang et al., 1999; Buijze et al., 2007) predicted a teres major tendon transfer to the insertion of the supraspinatus on the greater tubercle of the humeral head to mechanically maximize functional task performance. Anatomically, the teres major is an *ad*ductor and internal rotator of the arm. After transfer, the teres major is expected to contribute to arm elevation and exorotation (Celli et al., 1998). Although moderate to good functional results are reported for such reconstructive tendon transfer treatment (Celli et al., 2005), analysis of muscle function (changes), essential to comprehend its clinical successes, is not available.

We proposed that, as result of a rotator cuff tear the balance between glenohumeral stability and mobility of the shoulder is disturbed (de Groot et al., 2006; Steenbrink et al., 2006; Steenbrink et al., 2009a). The deltoids are believed to compensate lost rotator cuff elevation moments (McCully et al., 2007; Steenbrink et al., 2009a). The subsequent increase of cranially directed forces on the humeral head affect glenohumeral joint stability (Steenbrink et al., 2009a) and result in proximal migration (Graichen et al., 2005; van de Sande and Rozing, 2006) causing (painful) compression of the subacromial tissues. Muscles inserting on the humerus and generating downward directed forces, i.e. the teres major and latissimus dorsi, have been demonstrated to co-contract in order to compensate proximal migration of the humeral head (de Groot et al. 2006, Steenbrink et al., 2006, Steenbrink et al. 2009a). Divergent muscle activation clearly plays a role in the functional impairments observed in patients with cuff tears and is assumed to be an important variable affecting treatment outcome (Iannotti et al., 2006; Codsi et al., 2007; Irlenbusch et al., 2008a).

In addition to clinical outcome, we therefore assessed muscle function of the teres major, latissimus dorsi and the deltoids (medial part) before and after a teres major tendon transfer. We postulate that preoperative 'out-of-phase' *ad*ductor muscle activation of teres major and/or latissimus dorsi coincides with functional impairment. Relocating the teres major insertion should result in a post-surgical teres major activation during arm *ab*duction (elevation) forces instead of the typical *ad*duction component. 'Out-of-phase' latissimus dorsi activation is expected to reduce, due to the recovered stabilizing forces of the transferred teres major, while deltoid activation is not expected to change (Levy et al., 2008). After a teres major tendon transfer, optimized muscle activation is expected to result in improved clinical outcome.

5.2 Methods

Fourteen patients (10 male) with an average age of 61 years (range, 53-69) were included in the study between June 2005 and June 2007. All patients had MRI diagnosed rotator cuff tears larger than 4 cm with retraction and Goutallier grade 3-4 fatty degeneration excluding primary cuff repair (Goutallier et al., 1994). MRI patient characteristics are summarized in Table 5.1. All patients were treated with a teres major tendon transfer to the insertion of the supraspinatus and assessed within one month before and nine months (range, 7-11) after surgery. Ten healthy controls (5 male) with an average age of 25 years (range, 22-28) volunteered for norm electromyography (EMG) data collection.

The study was approved by the medical ethics committee of the Leiden University Medical Center and all participants gave written informed consent.

5.2.1 Surgical technique

Patients were positioned in a lateral decubital position. A curved incision was made at the posterior part of the axilla towards the humerus. After confirmation of an irreparable tear, the teres major was separated from the latissimus dorsi insertion and detached from the humerus. A second incision was made in the Langerhans lines at the posterocranial part of the humerus.

Table 5.1: Radiological/MRI characteristics of the patients. SSp: supraspinatus; IS: infraspinatus; SSc: subscapularis; TMn: teres minor; BL: biceps longum; AC: acromion-clavicular; +: affected; part: partially affected; -: not affected.

Patient	Side	SSp	IS	SSc	TMn	BL	Proximal migration humeral head	Retracted SSp	AC joint arthosis
1	L	+	-	-	-	-	+	+	+
2	R	+	part	-	-	-	+	+	-
3	L	+	-	part	-	-	-	+	-
4	L	+	+	-	-	-	+	+	-
5	R	+	+	+	part	+	+	+	+
6	R	+	part	-	-	-	+	+	-
7	R	+	-	+	+	+	+	+	+
8	R	+	+	-	-	-	+	+	+
9	R	+	part	-	-	+	+	+	-
10	R	+	+	-	-	+	+	+	+
11	R	+	part	-	-	-	+	+	-
12	R	+	part	-	-	-	+	+	-
13	L	+	+	-	-	-	+	+	+
14	R	+	+	+	-	+	+	+	+

The deltoid muscle was split and the teres major tendon was transferred underneath the posterior part of the deltoids and attached using two RC Mitek Anchors (DePuy Mitek inc., Warsaw, IN, USA) on the cranial supraspinatus footprint area. Postoperatively, a shoulder brace prevented internal rotations and after 6 weeks physical therapy was started.

5.2.2 Electromyography

During an isometric force task, bi-polar surface *EMG* was recorded for the teres major, latissimus dorsi and the deltoids (silver electrodes, inter-electrode distance 21mm, bandwidth 20Hz-500Hz). For the control group a DelSys system was used (Bagnoli-16, Boston, MA, USA, inter-electrode distance 10 mm, bandwidth 20Hz-450Hz). Electrode placement was similar to de Groot et al. (2004) and Meskers et al. (2004). After transfer, the teres major was palpated and the electrode placed on the middle of the muscle belly. Subjects were seated with their injured arm in a splint with the elbow in 90° flexion. The splint was attached to a 6DOF-force transducer (AMTI-300, Advanced Mechanical Technology, Inc., Watertown, MA, USA). The construction only allowed force exertions perpendicular to the longitudinal axis of the humerus (Fig. 5.1). The humeral plane of elevation was about 60° relative to the sagittal plane, the humerus was elevated about 45° and externally rotated with the lower arm about 30° relative to the horizontal plane. The force magnitude was set at the highest level at which the subject could comfortably fulfill an isometric force task in seven upwards directions (215°, 230°, 245°, 0°, 15°, 30°, 45°) and seven downwards directions (135°, 150°, 165°, 180°, 195°, 210°, 225°). The force task was controlled for direction and magnitude by visual feedback on a computer screen located in front of the subject. Sample rate of analog filtered EMG and force data was 1000Hz.

Muscle moment arms, represented in Fig. 5.2, were obtained from inverse kinematic model simulation (van der Helm, 1994) with experimental arm position as kinematic input (Steenbrink et al., 2009a). Muscle activation was qualified according to their moment arms, i.e. activation was either 'in-phase' or 'out-of-phase' with respect to its moment arm. For the teres major and latissimus dorsi, 'in-phase' activation was defined as activation during downwards arm force directions (*ad*duction) and 'out-of-phase' activation was defined as activation during the upwards arm force directions (*ab*duction). The teres major becomes an *ab*ductor after transfer (Fig. 5.2), and 'in-phase' activation then occurs while generating upwards arm forces. Deltoid activation is 'in-phase' with upwards arm forces. EMG at rest was subtracted from the EMG's during the force tasks. Two average EMG levels were determined for every muscle, i.e. one over the seven upwards and one over the seven downwards arm force exertion. Muscle *activation ratios* were calculated according Eq. 5.1:

$$AR_{muscle} = \frac{A^{IP}_{muscle} - A^{OP}_{muscle}}{A^{IP}_{muscle} + A^{OP}_{muscle}} \qquad [-1 \leq AR_{muscle} \leq 1] \tag{5.1}$$

where AR_{muscle} is the relative activation or *activation ratio* of *muscle* teres major (TMj), latissimus dorsi (LD) or deltoid (DE); AR = 1 indicates optimal 'in-phase' muscle activation and AR = -1 indicates worst 'out-of-phase' muscle activation. For AR = 0, activation is equal for up-and downwards arm force exertion; A^{IP} is the 'in-phase' muscle activity, contributing positively to the external moment according to the muscle moment arm; A^{OP} is the 'out-of-phase' muscle activity, contributing negatively to the external moment according to the muscle moment arm.

5.2.3 Clinical assessment

Maximum arm Range of Motion (RoM) was determined relative to the thorax (Meskers et al., 1998) for *ab*duction (RoM_{AB}), forward flexion (RoM_{FF}) and retroflexion (RoM_{RF}). External

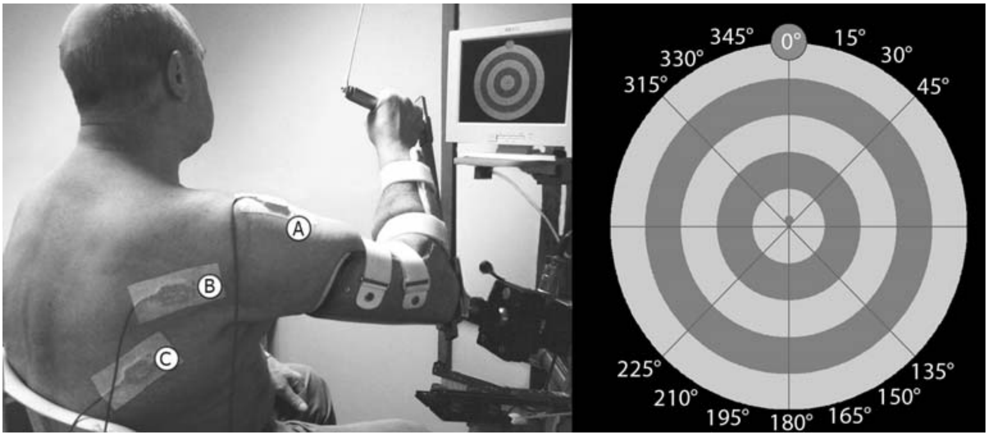

Figure 5.1: Experimental set-up; the patient is seated in front of a screen with his injured arm in a splint, which is connected to a force transducers. Surface *EMG* electrodes are positioned on the medial part of the deltoids (A), the teres major (B), and the latissimus dorsi (C). The patient exerts arm forces controlled by visual feedback of an arm force driven small circled cursor into a bigger circled target area. The target area is randomly located at seven upwards directions (215°, 230°, 245°, 0°, 15°, 30°, 45°) and seven downwards directions (135°, 150°, 165°, 180°, 195°, 210°, 225°), demanding respectively *ab*-and *ad*duction arm moment exertion.

rotation was measured at 0° humerus *ab*duction (RoM_{EXT}). All values were measured with an electromagnetic tracking device (Flock of Birds, Ascension Technology Corp, Burlington, VT, USA). External humerus rotation was defined 0° in the position at which the hand pointed forward and external rotation had a positive sign.

Pain was assessed using a 100mm Visual Analog Scale (*VAS*) both at rest (VAS_{rest}) and during Activities of Daily Living (VAS_{ADL}) (0: no pain; 100: worst pain ever imaginable); arm function was assessed using the *Constant Shoulder Score* (Constant and Murley, 1987).

F_{max} comprehended the highest determined force magnitude, recorded by the force transducer, which the subject could exert in all directions. Fext was the maximal arm force in external rotation, recorded by the force transducer in a 'locked' axial rotation set-up.

5.2.4 Statistics

Differences between *activation ratios* of patients and controls were statistically tested using the Student's t-test. Pre-and postoperative *AR*, *RoM*, *VAS*, *Constant Scores* and F_{max} were

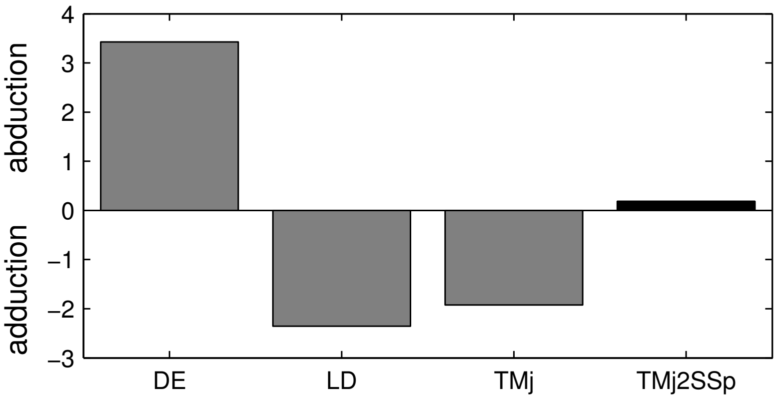

Figure 5.2: Representation of muscle moment arms obtained from inverse kinematic model simulation (van der Helm, 1994) in the experimental arm position (Steenbrink et al., 2009a). The columns represent the moment arms about the local x-axis, which is the *ab*duction/*ad*duction axis, for DE: deltoid (medial part); LD: latissimus dorsi; TMj: teres major; and TMj2SSp: teres major after transfer to supraspinatus insertion on the humeral head.

compared using the paired samples t-test. Linear regression was applied for each of the clinical variables as a function of AR_{TMj} and tested for significant slope coefficients. All tests were performed using SPSS 16.0 (SPSS Inc, Chicago, IL) with an alpha of 5%.

5.3 Results

Average duration of the teres major tendon transfer surgery procedure was 81 minutes (range 60-135 minutes). No complications were reported during surgery, nor postoperatively, nor during the protocolized physical therapy sessions. In concordance with other reports (Codsi et al., 2007; Pearle et al., 2006), no difficulties were encountered in isolating the teres major from the latissimus dorsi for transfer underneath posterior part of the deltoids. Sufficient teres major length allowed its transfer onto the greater tubercle of the humeral head (Pearle et al, 2006; Buijze et al., 2007). Thickness of the muscle-tendon unit did not compromise the subscapular nerve, which could risk a traction injury due to transfer after muscle transfer (Buijze et al., 2007).

Table 5.2: Pre-and post teres major tendon transfer clinical data, significant differences are indicated (*). *RoM*: range of motion; *AB*: *ab*duction; *FF*: forward flexion; *RF*: retroflexion; EXT: external rotation; *VAS*: visual analogue score for pain at rest and during activities of daily living (ADL); *Fmax*: maximal arm force in experimental setup; *Fext*: maximal external rotation force.

	RoM_{AB} (°)		**RoM_{FF} (°)**		**RoM_{RF} (°)**		**RoM_{EX} (°)**		**VAS_{rest} (mm)**		**VAS_{ADL} (mm)**		**Constant Score**		**Fmax (N)**		**F_{EXT} (N)**	
Patient	*pre*	*post*	*pre*	*post*	*pre*	*post*	*pre*	*post*	*pre*	*post*	*pre*	*post*	*pre*	*post*	*pre*	*post*	*pre*	*post*
1	91	110	77	98	31	34	4	15	81	11	53	0	22	31	10	20	2	20
2	104	143	97	130	35	39	12	45	72	5	45	4	47	79	10	30	8	7
3	90	117	76	85	22	21	6	10	53	51	76	34	24	54	20	20	10	13
4	20	18	19	28	41	38	7	10	63	12	6	0	35	42	10	20	4	9
5	128	140	120	124	40	30	-1	34	7	4	34	32	28	65	5	10	7	10
6	150	153	145	151	38	46	7	-29	38	0	74	0	58	77	10	10	5	10
7	44	70	45	78	45	37	21	25	62	0	32	0	26	64	10	20	8	10
8	59	134	50	120	39	49	14	34	48	8	4	0	19	42	10	20	5	10
9	93	103	90	109	40	46	17	37	74	0	66	0	35	79	10	20	15	20
10	163	170	144	167	36	38	30	12	45	0	23	0	78	78	50	50	7	8
11	96	112	109	117	53	50	13	36	71	34	82	33	23	49	20	40	13	13
12	52	50	44	67	17	23	-29	6	79	32	67	54	18	30	15	15	6	5
13	124	116	79	126	36	42	3	21	71	24	77	13	49	67	30	50	15	26
14	139	148	105	142	31	63	5	62	96	56	9	5	20	79	20	30	30	28
Mean	86	110	97	113	36	40	8	23	66	23	59	19	35	60	16	25	9	14
SD	38	37	42	42	9	11	13	22	15	21	21	22	18	18	12	13	6	7
P	0.012*		0.000*		0.190		0.033*		0.000*		0.000*		0.000*		0.002*		0.017*	

5.3.1 Activation Ratios

In the control group we observed positive *activation ratios* for all recorded muscles, AR_{TMj}, AR_{LD} and AR_{DE} (Fig. 5.3, Table 5.2). Pre-operatively in patients, we observed lower *activation ratios* for the deltoid muscle, AR_{DE}, compared to controls (95% confidence interval of the difference (CI_d): [0.11, 0.37], $p = 0.01$). Compared to controls, the *activation ratios* for the teres major and the latissimus dorsi, AR_{TMj} and AR_{LD}, were significantly lower compared to controls (95% CI_d: [0.51, 0.93], $p = 0.00$; 95% CI_d LD [0.50, 0.84], $p = 0.00$). After teres major tendon transfer the post-surgical AR_{TMj} changed significantly (95% CI_d [0.14, 0.40], $p = 0.01$). The positive *activation ratio* of the teres major, AR_{TMj}, corresponded with the muscle's new anatomical position inserting on the greater tubercle of the humeral head, contributing to the upwards directed arm forces. Postoperative *activation ration* of the latissimus dorsi, AR_{LD}, did not change compared to preoperative values (95% CI_d [-0.24, 0.06], $p = 0.22$), while postoperative *activation ratios* of the deltoid muscle, AR_{DE}, increased significantly (95% CI_d: [0.04, 0.26], $p = 0.01$).

Table 5.3: Mean muscle *activation ratios* (SD). Significant differences between controls and patients prior to teres major transfer are marked with a (*). Significant differences between patients prior to and after teres major transfer are marked with a (**).

	Control (n=10)	Patient (n=14)	
Muscle		*pre surgery*	*post surgery*
Teres major	0.64 (0.24)	-0.08 (0.6)*	0.28 (0.18)**
Latissimus dorsi	0.65 (0.19)	-0.01 (0.2)*	0.07 (0.27)
Deltoid	0.87 (0.07)	0.63 (0.2)*	0.78 (0.16)**

5.3.2 Clinical results

On average (n=14) patients improved significantly on all clinical outcome variables except for RoM_{RF} (Table 5.3). The mean postoperative *RoM* increased for *ab*duction (24°, SD 21°), forward flexion (16°, SD 10°) and external rotation (15°, SD 10°). Patients reported decreased pain at rest (-43mm, SD 22mm) and during *ADL* (-40mm, SD 25mm), and a functional increase on the *Constant Shoulder Score* of 25 SD 16 points. F_{max} and F_{ext} increased 9N (SD 7N), and 4N (SD 5N), respectively.

5.3.3 Linear regression AR_{TMj} to clinical outcome

The linear regression estimates and 95% CI's for the independent AR_{TMj} and the dependent clinical outcome variables RoM_{AB}, RoM_{FF}, RoM_{EXT}, RoM_{RF}, VAS_{rest}, VAS_{ADL}, $ConstantScore$, F_{max} and F_{EXT} are presented in Figure 5.4. The slope coefficients (β) for all parameters differed significantly from zero except for RoM_{RF} and F_{EXT}.

5.4 Discussion

This study evaluates clinical outcome and muscle function of the teres major, latissimus dorsi and the deltoids in patients with a glenohumeral cuff tear prior to and after a teres major tendon transfer to the supraspinatus footprint. The theoretical background for this analysis is the biomechanical conflict between elevation mobility and glenohumeral stability (Veeger and van der Helm 2007, Steenbrink et al 2009a) which is partly solved by the teres major transfer (de Groot et al. 2006). It is demonstrated that teres major function before surgery is pathological (de Groot et al. 2006, Steenbrink et al, 2006) and indeed contributes to the

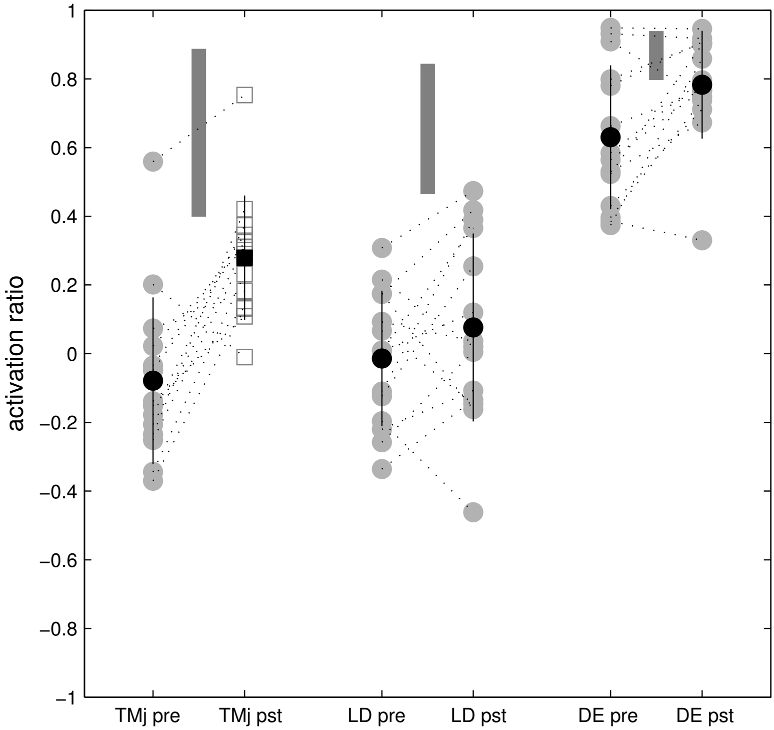

Figure 5.3: Mean *activation ratios* (±SD) of teres major (TMj), latisimus dorsi (LD) and the medial part of the deltoids (DE) for healthy subjects (95% confidence interval (vertical grey bars) and patients with cuff tears (filled circles (± -)) before (pre) and after (pst) teres major tendon transfer. Individual patient data is represented by grey filled circles and mean patients data by filled black circles. Mean patient data of the transposed teres major is represented by a filled black square and individual data by unfilled squares.

elevation moment after transfer. This study also provides evidence that teres major function before and after transfer relates to the predicted (Magermans et al., 2004a; Magermans et al., 2004b) and observed (Celli et al., 1998; Celli et al., 2005, this study) improvement of functional outcome after surgery.

The clinical results demonstrated the ‘moderate’ success of a teres major tendon transfer for patients with a glenohumeral cuff tear and functional improvement was comparable to those reported after a latissimus dorsi transfer (Gerber et al., 2006; Iannotti et al., 1996; Miniachi and McCloud, 1999; Warner et al., 2001). However, patients did not regain normal function, pain did not disappear completely in over 50% of the cases and results are highly variable. In order to identify significances from the large number of possible determinants (e.g. causal: habitual or traumatic; spatial: size and location of the lesions; temporal: instantaneous, chronic; secondary pathology: fatty degeneration; coordinative skills (Werner et al., 2008)), large cohort studies are required.

The biomechanical determinants of cuff lesions (Steenbrink et al., 2009a) and tendon transfers (Magermans et al., 2004a; Magermans et al., 2004b) define the borders of shoulder function which are expressed in other physiological determinants. Therefore we aimed at showing the counterproductive teres major activation before surgery and prove functional activation of the teres major after transfer. In order to quantify the mechanical contribution we applied a relative *EMG* measure, the *activation ratio*, assuming increased *EMG* contributing to non-linear muscle force increases within our isometrical measurement set-up (de Groot et al. 2004, Meskers et al. 2004). The combination of *EMG* parameters with muscle moment arms, obtained from model simulation (van der Helm, 1994), is suitable for studying muscle function (Gatti et al., 2007). This allowed us to quantify ’muscle function’ prior to and after teres major tendon transfer within a repeated measures design. Changes in the mechanical muscle function should at least partly be related to functional clinical outcome parameters. Activation of the transposed muscle (Iannotti et al., 2006; Irlenbusch et al., 2008a), the teres major in our case, is a prerequisite for the presumed success of tendon transfer surgery. We demonstrated distinguished teres major activation according to its new anatomical function, resulting in a positive AR_{TMj} after surgery, indeed indicating a functional transfer. The *activation ratio* did not exceed 0.4, illustrating muscle activity both during the ‘acquired’ *ab*duction task but also still during the ‘original’ *ad*duction task. Either the muscle compensates for forces and moments other than the *ad*duction moment during the *ad*duction task (glenohumeral joint comprises 3 rotational degrees of freedom) and/or the original activation pattern is not fully reversed in the newly obtained coordination pattern.

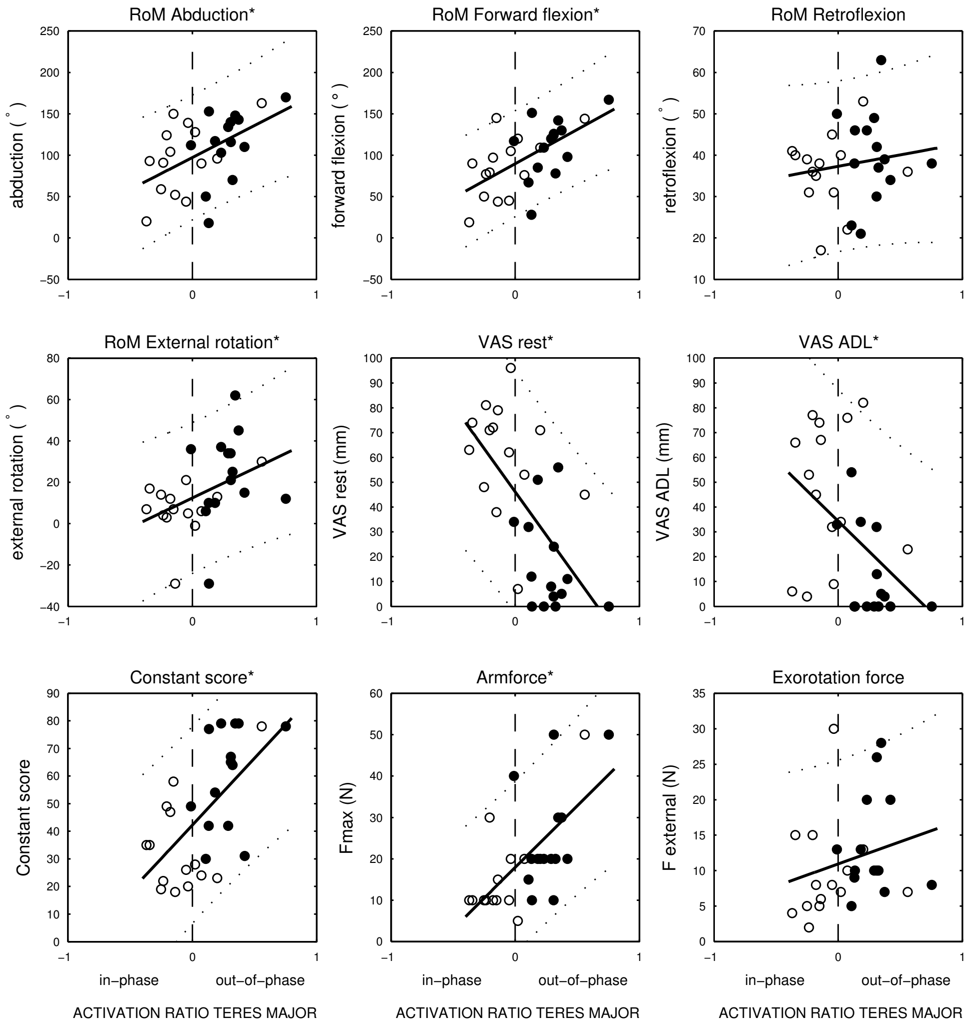

Figure 5.4: Linear regression of teres major *activation ratio* to clinical outcome variables. Preoperative measurements are marked with a open circle, and postoperative measurements are marked with a filled circle. Slope coefficients β which significantly differed from zero are marked with a * in the title of the subplot.

Although the control group was not age and gender matched, the observed differences between patients and controls were of such magnitude that they could not solely be explained by group differences. In contrast to healthy subjects, *activation ratios* of patients indicated preoperative ‘out-of-phase’ *ad*ductor muscle activation of the teres major and latissimus dorsi suggesting a compensation strategy for proximal migration of the humerus (Graichen et al., 2005; de Groot et al., 2006; Steenbrink et al., 2006a; Steenbrink et al., 2009a).

With regression analysis we found a significant linear relation between AR_{TMj} and most clinical outcome variables before and after surgery. Despite the small cohort of patients in this study, we demonstrated that teres major activation prior to and after surgery, at least partially, explains the variances in functional and clinical outcome. To our knowledge this study is the first to find evidence for a biomechanical relation between a surgical intervention and its clinical outcome. The effect of changed teres major function on clinical outcome after transfer supports the biomechanical hypothesis about the role of the teres major in arm mobility and glenohumeral stability in patients. Although precaution should be made when extrapolating results to dynamic conditions, preoperative ‘out-of-phase’ teres major activation may constrain shoulder and ‘in-phase’ activation of the transposed teres major appears to support functionality.

The transferred teres major contributes to arm *ab*duction and deltoid muscle forces are likely to decrease. Subsequently, the upward directed forces in the glenohumeral joint reduce and less co-contraction of the remaining *ad*ductor (latissimus dorsi) is required. The postoperative ‘out-of-phase’ latissimus dorsi activation indeed seems to be decreased, however not statistically significant. Despite the low *activation ratio* compared to controls, AR_{DE} in patients preoperatively displayed evident ‘in-phase’ muscle function. The AR_{DE} increased after the teres major tendon transfer, either through increased deltoid arm *ab*duction moment generation or decreased deltoid activity during *ad*duction. Because AR_{DE} in controls is even higher, the latter option is presumed.

As the surgery intended, we indeed found an increase of external rotation arm force. The absence of a significant relation with AR_{TMj} is not surprising as *ab*duction and *ad*duction tasks are compared to calculate *activation ratios*, and not internal and external rotation.

A possible side-effect of muscle transfers in general may be the deterioration of original function of the transposed muscle. Because of its substantial moment arm, deficits in arm retroflexion/*ad*duction were found after a latissimus dorsi tendon transfer, which manifested by early fatigue of the arm (Spear et al., 2006). This may induce functional problems in elderly when dependant on active arm *ad*duction/extension when rising from a chair or using crutches. After a teres major tendon transfer we observed no deficits in maximum arm retroflexion. Although advisable, identification of possible functional adverse effects after tendon transfer surgery was not the subject of this study.

5.5 Conclusion

In this evaluation of a teres major tendon transfer in patients with irreparable rotator cuff lesions we found functional and clinical improvements and provide evidence that the teres major is functionally activated after transfer surgery.

This study also provides evidence for the biomechanical relation between teres major function before and after surgery with the observed functional and clinical improvements. The preoperative deteriorated arm *ab*duction function was associated with pathological 'out-of-phase' *ad*ductor muscle activation of both the teres major and latissimus dorsi. This is assumed to be an attempt to accommodate for better glenohumeral stability in the cranially migrating humeral head. After surgery patients were able to activate the teres major in correspondence with its new anatomical function, delivering a stabilizing force component at the humeral head. This study illustrates the importance of biomechanical force and moment balance in rotator cuff pathology and tendon transfer surgery.