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Cranial humerus translation, Deltoid activation, Adductor co-activation and rotator cuff disease - Different patterns in rotator cuff tears, subacromial impingement and controls -

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Abstract

**Background:** Arm adductor co-activation during abduction has been reported as a potential compensation mechanism for a narrow subacromial space in patients with rotator cuff dysfunction. We assessed differences in acromiohumeral distance at rest and the amount of humerus translation during active abduction and adduction in patients with rotator cuff tears (n=20) and impingement (n=30) and controls (n=10), controlled for Deltoid, Pectoralis Major, Latissimus Dorsi and Teres Major activation (electromyography).

**Methods:** During the acquirement of shoulder radiographs, subjects performed standardized isometric arm abduction and adduction tasks. EMGs were normalized between -1 and 1 using the “Activation Ratio”, where low values express (pathologic) co-activation, e.g. adductor muscle activation during abduction.

**Findings:** In patients with cuff tears mean rest acromiohumeral distance was 7.6mm (SD=1.6): 3.5mm narrower compared to patients with impingement (95%-CI: 2.4-4.5) and 1.3mm narrower compared to controls (95%-CI: -0.1-2.7). Both during abduction and adduction tasks, cranial translation was observed with equal magnitudes for patients and controls, with average values of 2.3 and 1.7mm, respectively. Where patients with cuff tears had lower adductor Activation Ratios (i.e. more adductor co-activation during abduction), no association between abductor/adductor muscle activation and acromiohumeral distance was found.

**Interpretation:** The subacromial space is narrower in patients with rotator cuff tears compared to patients with impingement and controls. We found additional subacromial narrowing during isometric abduction and, to a lesser amount, during adduction in all subjects and more adductor co-activation in patients with cuff tears. We found no association between subacromial space and activation of the Deltoid and main adductors.

**Keywords:** Rotator Cuff; Shoulder Impingement Syndrome; Electromyography; Diagnostic Techniques and Procedures; Adductor Co-activation
1. Introduction

The incidence of shoulder complaints in general practice is high, with 22 per 1000 registered patients per year.\(^1\) 44-65% of shoulder symptoms are diagnosed as "Subacromial Impingement Syndrome" (SIS)\(^2,3\) and 36% of subjects with shoulder symptoms have been demonstrated to have rotator cuff tears.\(^4\) Both conditions show similar symptoms, including pain and loss of arm abduction force, although symptoms are generally worse in patients with rotator cuff (RC) tears.\(^5,6\) Some report that both are stages of the same condition, where SIS may progress to a RC tear due to muscle and tendon degeneration.\(^6-10\) We assessed similarities and differences in objective biomechanical signs suggestive for RC dysfunction in patients with SIS or RC tears and controls.

A narrow subacromial space due to a cranial position of the humerus relative to the acromion has been radiologically demonstrated in patients with RC tears.\(^11-14\) A narrow subacromial space has been associated with shoulder pain, larger RC tear sizes, progression of RC tears to multiple tendons and RC degeneration, and has been reported as a negative prognostic factor for (surgical) treatment.\(^11-17\) Additional narrowing of the subacromial space (i.e. cranial humerus translation) during active arm abduction has been reported on radiographs and magnetic resonance imaging (MRI) acquired in healthy subjects, and patients with RC tears or SIS.\(^18-21\) In these studies, it was postulated, that RC deficit patients show more cranial humerus translation than healthy subjects and that this cranial translation may be a diagnostic tool or an objective clinical outcome measure.

Subacromial narrowing is the subject of an increasing number of publications and is more and more applied in clinical practice, but its underlying mechanisms are remain unclear. RC muscles play a key role in glenohumeral (GH) stabilization and arm mobility; in the healthy shoulder a perfect compromise is assumed between mobility and stability.\(^22\) In patients with RC tears, GH joint mechanics are disrupted as one or more RC muscles are dysfunctional. This may lead to 1) a compensatory increase in Deltoid activity;\(^23-25\) 2) GH (micro-)instability;\(^25\) 3) excessive cranial humerus translation with the activation of arm abductors\(^11,12,18,19,21,25-29\) and subsequent pain. It has been hypothesized that co-activation of specific adductor muscles with downwardly directed lines of action (e.g. Teres Major and Latissimus Dorsi) is a compensation mechanism to counteract this excessive cranial translation during abduction in patients with RC tears.\(^24,25,30-32\)

The actual relation between cranial humerus translation, pain and adductor co-activation as a potential protective mechanism has been scarcely investigated experimentally,\(^24,30-32\) specifically for patients with SIS, in whom the RC is still anatomically functional. Patients with RC tears can be regarded as ultimate
demonstrators for RC dysfunction. If translation and adductor co-activation are also found in patients with SIS, disrupted GH joint mechanics might exist in these patients, despite intact RC muscles. This would indicate that in addition to the many reported etiologies of SIS, decreased RC function and altered biomechanics might play a role as well.

We investigated acromiohumeral distance ($AH$) on radiographs acquired during electromyography(EMG)-recorded isometric abduction, adduction and rest tasks in patients with RC tears, patients with SIS and controls. Our primary goals were to 1) assess $AH$ at rest and humerus translation ($\Delta AH$) during abduction and adduction force tasks, 2) assess (pathologic) co-activation of Deltoid, Latissimus Dorsi, Teres Major and Pectoralis Major, and 3) assess the association between $AH$, Deltoid activation and adductor (co-)activation. We hypothesized that 1) in patients baseline (rest) $AH$ is smaller and $\Delta AH$ larger compared to controls; 2) patients apply more adductor co-activation during abduction compared to controls; and 3) Deltoid activation is negatively and adductor co-activation is positively related to $AH$ and $\Delta AH$. We expect healthy controls, patients with SIS and patients with RC tears to order along the scales of subacromial narrowing and adductor co-activation.

2. **Methods**

2.1 **Subjects**

Consecutive patients with a painful shoulder and a full-thickness RC tear (Supraspinatus and/or Infraspinatus) and patients diagnosed with SIS were included in this study during the period of April 2010 to April 2012. In addition, 10 controls were recruited in September 2012. Inclusion criteria for the controls were: age between 35 and 60 years (minimizing the prevalence of eventual asymptomatic cuff tears and age differences between controls and patients), no present shoulder complaints and no history of shoulder complaints treated with physical therapy, NSAIDs, injections, or surgery. Controls were assessed by an MD for eventual shoulder symptoms.

Patients with SIS or RC tears had to have a positive Neer impingement test, a positive Hawkins test and diffuse unilateral anterosuperior shoulder pain for >3 months in combination with one or more of the following criteria: pain with overhead activities, abduction, retroflexion and/or internal rotation (e.g. closing the door, putting on jacket); pain at night or incapable of lying on the shoulder; diffuse pain at palpation of the greater tuberosity; disturbed scapulohumeral rhythm; classic painful arc; positive Yocum test; positive full or empty can test.
Patients with SIS had to be aged between 35 and 65 years. Exclusion criteria for SIS were partially based on an MRI arthrogram and standard anteroposterior (AP) shoulder radiographs: no calcific tendinitis, full-thickness RC tear, intra-articular or bony lesions (Hill Sachs, (old) fractures, tumors), labrum abnormalities, capsular or ligamentous tears/avulsions, superior labrum tear from anterior to posterior (SLAP lesion), pulley lesion, Biceps tendinitis or tear, os acromiale, cartilage lesions, or bony cysts. Patients with RC tears had to be aged 50 years and older. They were symptomatic and had a standard AP shoulder radiograph and MRI arthrography or ultrasound (US)-proven full-thickness RC tear, without a Subscapularis tear and other shoulder pathologies. Subjects were furthermore excluded in case of insufficient Dutch language skills or no informed consent, present physical problems influencing muscle activation and arm mobility (other than the present shoulder condition), any form of inflammatory arthritis of the shoulder, glenohumeral or symptomatic acromioclavicular osteoarthritis, a history of fracture, dislocations, or surgical interventions of the shoulder, clinical signs of cervical radiculopathy and frozen shoulder syndrome (<90° of passive abduction and external rotation). Radiographic data on acromiohumeral distance in the RC tear group were previously published. In the current study these data are re-assessed with permission of the authors. Additionally, we included simultaneously acquired EMG-recordings in the analyses and used the data of this group with another goal: to compare acromiohumeral distance in three subject groups and to relate the acromiohumeral distance with muscle activation patterns, including adductor co-activation.

Patients were clinically assessed using the Western Ontario Rotator Cuff score (WORC) and the Constant Score (CS). The accredited local Medical Ethics Committee (METC, Leiden University Medical Center) approved all stages of the study according to the Medical Research Involving Human Subjects Act and written informed consent was obtained from all participants (Dutch Trial Registry NTR2283).

2.2 Experimental set-up

Included subjects performed standardized isometric arm abduction and adduction tasks of equal force magnitude by pressing against a single axis force sensor (Penko Engineering, Ede, the Netherlands) with the arm alongside the body, using a previously introduced experimental set-up with visual feedback. (Figure 1) Thus, the task forces were perpendicular to gravitational forces. This set-up was specifically developed to enable reproducible and isometric arm tasks and to acquire standard shoulder radiographs in combination with EMG. Accordingly, AP shoulder radiographs were acquired during rest and during isometric abduction and adduction force tasks to obtain acromiohumeral distance in combination with...
Figure 1. Experimental set-up.
Subjects were in standing position with the target arm in external rotation at his/her side (i.e. hand in frontal plane), enabling the use of this set-up during concomitant acquirement of standard shoulder radiographs for clinical or scientific purposes. The arm was attached to a 1-dimensional force transducer at the wrist. In this set-up, subjects performed EMG-recorded isometric abduction and adduction force tasks.

EMG for each task. Before the radiograph series, maximum voluntary force (MVF) was measured for abduction and adduction for each subject. Final subject-specific force task magnitude was 60% (±3.75% tolerance) of the minimal value of adduction and adduction MVF. All subjects performed at least one practice round and a series during which the radiographs were acquired.
Patients were assessed on their affected arm. For healthy subjects, the investigational side was determined by randomization (computer generated randomisation list) preceding inclusion.
2.3 Radiographs and humerus translation

The force controlled shoulder radiographs with simultaneously recorded EMG were acquired in a standardized setting. Arm position was constant during all tasks for each subject: the upper body was rotated 30° from the frontal plane towards the Röntgen focus beam with the arm at the subjects’ side and the hand in the frontal plane with the palm facing forward.33, 36

Radiograph quality was on-site controlled for using prescribed criteria33 and eventually re-acquired. On each radiograph, acromiohumeral distance (AH) and humerus translation (ΔAH) were assessed. For AH, the distance between the most cranial articular cortex of the humeral head and the caudal cortex marking of the caudal surface of the acromion was measured in millimetres.26, 28, 29 Task specific humerus translation was calculated from the differences between rest AH and abduction or adduction AH, obtaining ΔAH_{ab} and ΔAH_{ad}, respectively. When the necessary anatomical landmarks could not be identified, the measurement could not be performed and was reported as missing.

2.4 Electromyography and adductor co-activation

During the rest, abduction and adduction tasks, EMG of 3 shoulder adductors (Pectoralis Major, clavicular part (PM); Teres Major (TM); Latissimus Dorsi (LD)) and the main shoulder abductor (Deltoid, medial part (DM)) were recorded with bipolar surface EMG equipment (DelSys system Bagnoli-16, Boston, MA, USA, inter-electrode distance 10mm, bandwidth 20–450 Hz) as described previously.36 As absolute magnitude of EMG-signals is hard to interpret and cannot be compared between subjects or related to AH, EMG-recordings were expressed 1) relative to Maximal Voluntary Contraction EMG (MVC) and 2) in Activation Ratios. For this purpose, EMG was rectified (rEMG) and averaged (aEMG). Muscle activation during tasks (A_{muscle}) was determined by subtracting the rest aEMG from the active aEMG during abduction and adduction, respectively. EMG quality (signal-to-noise-ratio) was controlled for: if rEMG was less than 2 times more active during tasks compared to rest activity, the concerning measurement was not included in statistical analyses. rEMGs were normalized to MVC for each task, muscle and subject. Additionally, the Activation Ratio was calculated, which combines the (absolute/not normalized) rEMGs of abduction and adduction tasks, in order to quantify muscle specific activation during agonist and antagonist tasks. For each muscle and subject, the following formula was applied, Eq. 1:

\[
AR_{\text{muscle}} = \frac{A_{\text{muscle}}^{\text{op}} - A_{\text{muscle}}^{\text{op}}}{A_{\text{muscle}}^{\text{p}} + A_{\text{muscle}}^{\text{op}}} \quad [-1 \leq AR_{\text{muscle}} \leq 1]
\]
where $A_{\text{muscle}}^{\text{IP}}$ is ‘in phase’ or agonist muscle activation (DM activation during abduction and TM, PM and LD activation during adduction) and $A_{\text{muscle}}^{\text{OP}}$ is ‘out-of-phase’ or antagonist muscle activation (DM activation during adduction, or TM, PM and LD activation during abduction, i.e. pathologic co-activation).\(^{32,36}\) The *Activation Ratios* of most muscles in healthy subjects are positive and close to 1. In case of substantial antagonist activation of specific arm adductors during *abduction* tasks (adductor co-activation), as has been previously described for the LD and TM in patients with RC tears, the *Activation Ratios* of these adductor muscles are expected to be close to zero or even negative.\(^{32}\)

### 2.5 Statistics

Demographic data and clinical scores (available in patients) were expressed in means and standard deviations or medians and ranges where appropriate. For radiographic measures, the mean $AH$’s (for rest, abduction and adduction) and the $\Delta AH_{ab}$ and $\Delta AH_{ad}$ in the three groups were all assessed using one-way ANOVA analyses. A similar approach was applied for the MVC-normalized rEMGs during rest and the *Activation Ratios* during abduction and adduction for the four muscles in patients from the three groups. Multivariate Mixed Model analysis for repeated measures was applied to study the association between $AH$ (dependent variable) and disease status (control, impingement, RC tear), task (rest, abdution, adduction) and the MVC-normalized muscle activations of DM, PM, LD and TM. 

P-values of $\leq 0.05$ were considered statistically significant. Analyses were processed using PASW Statistics 20.0 (IBM Inc., Chicago, Illinois, USA). Multivariate analyses were processed using R 2.15.2.

### 3. Results

60 Subjects were included: 20 patients with RC tears, 30 patients with SIS and 10 controls. Two patients with SIS were excluded due to hardware problems during the experiments, leaving 58 subjects for analyses.(Table 1)
Humerus cranialisation and adductor co-activation

<table>
<thead>
<tr>
<th>Baseline characteristics</th>
<th>SIS</th>
<th>RC tear</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>n=28</td>
<td>n=20</td>
<td>n=10</td>
<td></td>
</tr>
<tr>
<td>Age (yrs)</td>
<td>50.1 [1.6]</td>
<td>65 [9.8]</td>
<td>50.2 [6.6]</td>
</tr>
<tr>
<td>Gender (male/female)</td>
<td>11/17</td>
<td>11/9</td>
<td>5/5</td>
</tr>
<tr>
<td>Affected side (right/left)</td>
<td>17/13</td>
<td>12/8</td>
<td>6/4</td>
</tr>
<tr>
<td>Dominant side affected</td>
<td>18 (64%)</td>
<td>18 (90%)</td>
<td>NA</td>
</tr>
<tr>
<td>Baseline clinical scores</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WORC</td>
<td>61.7 [14.8]</td>
<td>57 [22]</td>
<td>NA</td>
</tr>
<tr>
<td>Constant Score</td>
<td>76.9 [8.5]</td>
<td>62 [15]</td>
<td>NA</td>
</tr>
</tbody>
</table>

Table 1. Demographic data of patients and controls. SIS, subacromial impingement syndrome; RC, rotator cuff; WORC, Western Ontario Rotator Cuff index [SD]: [Standard Deviation]

<table>
<thead>
<tr>
<th>Measurement</th>
<th>RC tear</th>
<th>SIS</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean AH at rest</td>
<td>7.6 (6.90 - 8.39)</td>
<td>11.1 (10.40 - 11.83)</td>
<td>8.9 (7.55 - 10.31)</td>
</tr>
<tr>
<td>Mean ΔAHab</td>
<td>2.6 (1.86 - 3.39)</td>
<td>2.3 (1.53 - 3.06)</td>
<td>2.1 (1.46 - 2.68)</td>
</tr>
<tr>
<td>Mean ΔAHad</td>
<td>1.0 (0.29 - 1.79)</td>
<td>1.1 (0.52 - 1.73)</td>
<td>0.8 (-0.02 - 1.60)</td>
</tr>
</tbody>
</table>

Table 2. Distance between humerus and acromion at rest, and amounts of cranial humerus translation during abduction and adduction in patients with RC tears, patients with SIS and controls. AH, acromiohumeral distance (at rest); ΔAH, difference in acromiohumeral distance during abduction (ab) or adduction (ad) compared to rest; 95%-CI, 95% Confidence Interval; RC, Rotator Cuff; SIS, subacromial impingement syndrome

3.1 Acromiohumeral distance
Two adduction radiographs needed to be reacquired in patients with RC tears, while not fulfilling the pre-set quality criteria. Furthermore, one adduction radiograph could not be assessed in a patient with SIS.

Mean AH at rest condition was 7.6mm (SD=1.60) in patients with RC tears, 11.1mm (SD=1.84) in patients with SIS and 8.9mm (SD=1.92) in controls. (Table 2, Figure 2) Average $AH_{rest}$ was significantly different in the three subject groups (p<0.001). Post hoc analyses revealed that in patients with RC tears mean $AH_{rest}$ was 3.5mm smaller (95%-CI: 2.4-4.5, p<0.001) compared to patients with SIS, and 1.3mm smaller (95%-CI: -0.1-2.7, p=0.07) compared to controls. Mean $AH_{rest}$ for patients with SIS was 2.2mm larger (95%-CI: 0.9-3.5mm, p=0.002) compared to controls.

Also during abduction (p<0.001) and adduction (p<0.001), AH was significantly different between the three groups. In post-hoc analyses, mean AH during abduction and adduction was significantly lower in patients with RC tears compared to patients with SIS, with differences of 3.8mm (95%-CI: 2.6-5.0) and 3.4mm (95%-CI: 2.2-4.6), respectively. Additionally, AH was significantly lower in patients with RC tears compared controls: 1.8mm (95%-CI: 0.3-3.4) and 1.5mm (95%-CI: 0.0-3.1), respectively.
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Figure 2. Acromiohumeral distance (AH) during rest and the isometric active abduction and adduction tasks for all subject groups. Overall, AH was narrower in patients with RC tears compared to controls and wider in patients with SIS. All subject groups showed similar amounts of cranial translation relative to rest during the abduction and adduction tasks.

All groups showed significant cranial humerus translation during the active tasks, except for the control group during adduction. Mean translations for the three groups ranged between 2.1 and 2.6mm for $\Delta AH_{ab}$ (abduction) and between 0.8 and 1.1 for $\Delta AH_{ad}$, and were not significantly different between the subject groups. (Table 2)

3.2 Muscle activation
Muscle EMG at rest, normalized to MVC, is displayed in Figure 3. Overall, there was more rest activity in patients than in controls. Post-hoc analyses revealed that for PM, there was significantly more rest activity in patients with RC tears compared to controls ($p=0.007$) and patients with SIS ($p=0.04$). For LD, there was significantly more activity in patients with RC tears compared to controls ($p=0.04$).

Mean AR's in patients with RC tears, assessing “out-of-phase” muscle activation (lower values), ranged from 0.42 to 0.58 for the adductors. For the abductor (DM), AR was 0.72 in this group. Average SIS AR for TM was 0.51. AR's for the DM and the LD and PM adductors ranged from 0.69 to 0.72. In controls, mean AR's ranged from 0.72 to 0.78 for DM and the adductors LD and PM. Mean TM AR in controls was 0.41. (Figure 4)
Overall, there were no significant differences between AR's in the three groups with one-way ANOVA analyses. With post-hoc analyses the AR of the PM was significantly lower in patients with RC tears compared controls: 0.53 vs. 0.79, leading to a mean difference of 0.26 (95%-CI: 0.03-0.24, p=0.03).

3.3 Relation between acromiohumeral distance, muscle activation and disease status

The alleged association between AH and muscle activation was assessed in multivariate mixed model analyses for repeated measures in each subject, leading to significant effects of disease status (control, SIS, RC tear) and performed task (rest, abduction, adduction) on AH. (Table 3) For disease status, AH was largest for patients with SIS, followed by controls and patients with RC tears, respectively. For performed tasks, AH was smallest during abduction, followed by adduction and rest. We found no significant association of muscle activations of DM, LD, PM or TM on AH. (Table 3)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Effect Size</th>
<th>95%-CI</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>9.20</td>
<td>8.1 - 10.3</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Disease status</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SIS</td>
<td>1.81</td>
<td>0.52 - 3.10</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>RC tear</td>
<td>-1.47</td>
<td>-2.83 - -0.10</td>
<td>0.04</td>
</tr>
<tr>
<td>Control</td>
<td>Ref.</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Task</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Abduction</td>
<td>-2.29</td>
<td>-3.23 - 1.36</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Adduction</td>
<td>-1.40</td>
<td>-2.58 - -0.22</td>
<td>0.02</td>
</tr>
<tr>
<td>Rest</td>
<td>Ref.</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Muscle Activation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DM</td>
<td>-0.25</td>
<td>-2.82 - 2.32</td>
<td>0.85</td>
</tr>
<tr>
<td>LD</td>
<td>0.80</td>
<td>-1.89 - 3.50</td>
<td>0.56</td>
</tr>
<tr>
<td>PM</td>
<td>0.86</td>
<td>-1.57 - 3.30</td>
<td>0.48</td>
</tr>
<tr>
<td>TM</td>
<td>-0.35</td>
<td>-3.09 - 2.39</td>
<td>0.80</td>
</tr>
</tbody>
</table>

Table 3. Multivariate mixed model analyses with AH as dependent variable and disease status, performed task and the MVC-normalized muscle activations of DM, PM, LD and TM as independent variables. Disease status and task had significant effects on AH. Patients with SIS had on average a larger AH than controls, whereas patients with RC tears had a smaller AH. Both isometric active abduction and adduction lead to a smaller AH. We found no significant effects of muscle activations on AH.
Figure 3. Muscle activations and 95%-CI during rest tasks for each muscle and subject groups, normalized to MVC EMGs. Overall, rest activity was higher in the patient groups compared to controls.

Figure 4. "Out-of-phase" muscle activation during abduction and adduction for all subject groups and all muscles, expressed in Activation Ratios (AR). Lower AR's indicate more pathologic activation, e.g. adductor co-activation during abduction.
4. Discussion and conclusions

This study reports on muscle activation and the distance between humerus and acromion at rest and during isometric abduction and adduction tasks in patients with RC tears, patients with SIS and controls. At rest, the acromiohumeral distance (AH) was narrowest in patients with RC tears. During active abduction, and to a lesser amount during adduction, cranial humerus translation was observed relative to rest in all subject groups, without statistically significant differences between the three groups. The rest activities of the Pectoralis and Latissimus Dorsi adductor muscles were larger for the patient groups. The EMG Activation Ratios of adductor muscles did not clearly indicate more pathologic activation (i.e. lower Activation Ratios) in patient groups compared to the controls, except for the Pectoralis and Latissimus Dorsi muscles in patients with RC tears, indicating a loss of muscle specific activation (i.e. adductor co-activation during arm abduction). We did not find an association between muscle (co-)activation and cranial humerus translation.

4.1 Acromiohumeral distance at rest
The smallest AH in rest we found in patients with RC tears, coincides with previous reports for RC deficit shoulders. This phenomenon has been related with shoulder pain, progression of RC tear size, multiple torn RC tendons and RC muscle degeneration in the literature. Some studies suggest a small AH to be an indicator for chronic massive RC tears. For patients with SIS, the average AH was not smaller than observed in controls, in contrast to our hypothesis. Possibly, actual full-thickness RC tearing needs to be present before an evidently narrower subacromial space in rest ensues. In support of this, Keener and colleagues found differences in AH between 1) patients with asymptomatic tears and symptomatic tears and 2) between patients with full-thickness tears and massive posterosuperior (i.e. Supraspinatus and Infraspinatus) RC tears. Another explanation is that there could be thickened RC tendons and bursa tissue in patients with SIS due to a subacromial inflammatory reaction, preventing the observation of an evidently smaller AH compared to controls despite potential RC deficiency. Subacromial filling may play an important role in determining the distance between acromion and humerus.

4.2 Cranial humerus translation during active tasks
Cranial humerus translation (ΔAH; additional narrowing of AH during active tasks compared to rest) was most evident during isometric abduction for all subject groups. Similarly, others found significant cranial translation at different elevation angles during active abduction in patients with SIS or RC tears. However, the currently applied set-up has the advantage that a standard elevation angle
and isometric tasks are applied for all subjects, improving the abilities to compare subjects.\(^{33}\) It has been suggested that cranial translation during abduction is caused by Deltoid activation.\(^{18,19,38}\) In patients with RC tears, there is suboptimal GH stabilization due to the torn RC\(^\text{25}\) and increased Deltoid activation, compensatory to lost RC function.\(^{23-25}\) In theory, this can cause excessive cranial translation of the humerus in patients, leading to (painful) compression of subacromial tissues.\(^{12,19,25}\) However, we found no differences in the absolute amounts of translation in the three groups, covering a complete range of subjects from symptomatic patients with RC tears, to patients with SIS with an intact RC and asymptomatic controls. But relative to rest AH, narrowing was most prominent in patients with RC tears, suggesting the largest subacromial strains in this group during abduction.

Surprisingly, there was not only cranial translation during arm abduction tasks, but also during arm adduction in all groups. Although the caudally directed TM and LD are primarily active during adduction, this did not lead to an average net caudalisation of the humerus. It is plausible that only limited activity of the Deltoid with its large Physiological Cross Sectional Area (PCSA) relative to the TM and the LD leads to cranial translation even during adduction tasks.

### 4.3 Linking AH and adductor co-activation

Hence, we found group differences between AH measures at rest, but not with the absolute \(\Delta AH\) measurements assessing cranial translation during tasks. This raises the question whether isometric active abduction and adduction radiographs have any additional value in clinical and scientific research. This all notwithstanding, e.g. 2.6mm humerus translation with a rest AH of 7.6mm as observed in patients with RC tears, i.e. a strain of 34%, might have more consequences than 2.1-2.3mm translation in patients with SIS or controls with their larger rest AH, i.e. strains of 20.7% and 23.6% respectively. A possible explanation for the similar amounts of AH narrowing in the three groups, despite the theoretical excessive narrowing in patients with RC tears, is adductor co-activation. Several simulation and EMG studies reported adductor activation during abduction (adductor co-activation) in RC patients, in particular for caudally directed adductors as the TM and LD, supposedly limiting subacromial narrowing by pulling the humerus down.\(^{24,25,30-32}\) We did find significantly higher adductor activation (relative to MCV) in rest in patients with RC tears compared to patients with SIS and controls. But this might partially be explained by somewhat lower maximum voluntary forces and subsequent MVC values in patients (data not shown). There also appeared to be relatively more adductor co-activation, expressed in lower Activation Ratios during abduction in patients with RC tears compared to patients with SIS (LD, PM, TM) and controls (LD, TM), but these differences were not statistically significant.
4.4 Adductor co-activation in patients with RC tears or SIS

In a previous study assessing controls and patients with RC tears with the same experimental set-up, we defined an AR of minimal 0.30 points lower compared to average control AR's is indicative for pathologic co-activation, leading to cut-off values of 0.59 for the DM, 0.48 for PM, 0.49 for LD and 0.38 for TM for this set-up. In the patients with RC tears of the current study, mean AR's of all adductors (PM, TM, LD) were around previously reported pathologic AR cut-off values. For patients with SIS, only AR of the TM was around the reported pathologic cut-off values. Although the RC is not torn in patients with SIS, tendinitis and partial tears can lead to impaired RC function and increased DM activation. Potentially, this causes (excessive) upwardly directed forces on the humerus during abduction, which can be compensated by co-activation of only the TM in patients with SIS, where co-activation of several adductors is required to maintain glenohumeral stability in patients with RC tears. Hence, adductor co-activation might be an indicator for RC dysfunction in general, instead of an indicator for RC tears specifically.

4.5 Unexpected results in the control group

The results of AH and adductor co-activation for patients with SIS or RC tears were overall as hypothesized, but we found unexpected results for the relatively small control group. AH in rest was not largest in controls and some controls showed adductor co-activation, in contrast to controls in our previous study with the same set-up. The current controls where older than in the previous study and their RC status was not assessed with imaging, in contrast to the patients' RC status. It is plausible that some controls had an asymptomatic (early stage) RC tear, with consequent adductor co-activation; the prevalence of asymptomatic RC tears has been reported between 4% and 80% and increases with aging. Furthermore, adductor co-activation might be related with aging, although previous studies have not supported this. Future research on asymptomatic controls of various age groups with ultrasound or MRI evaluation is needed to gain more insight in adductor co-activation and its alleged association with RC dysfunction.

4.6 Linking abductor and adductor muscle activation with AH in patients and controls

In this study we were able to simultaneously record EMG and subacromial translation in patient groups and controls. Combining all EMG recordings and AH measurements in multivariate analyses, disease status and exerted task had significant effects on AH. Similar to the ANOVA results, patients with SIS had on average a larger AH and patients with RC tears a smaller AH, compared to controls. AH was smaller during abduction and, to a lesser extent, adduction. We found no significant effects of
muscle activations on $AH$. We may conclude that $AH$ cannot simply be derived from the relative activation of the abductors and adductors, assuming an isometric linear relation between $AH$ and EMG. Assessing muscle forces, joint reaction forces and $AH$ additionally requires e.g. individual anatomy, including tendon thickness, bursa thickness, (subacromial) tissue stiffness, PCSA values and force directions of all contributing muscles, which were obviously not available in this study. Alternatively, affecting adductor co-activation by administering a subacromial injection with anaesthetics as has been applied in patients with RC tears could give more insight in the role of adductor co-activation with regard to subacromial narrowing.

4.7 Strengths and weaknesses

The strengths of this study include the comparison of three moderately large and well-defined groups, covering a broad range of rotator cuff (dys)function, the use of objective outcome measures ($EMG$, $AH$ and $\Delta AH$) and the use of a newly developed and validated set-up with a comprehensible measure for EMG-recordings ($AR$). Additionally, this is the first study assessing the association between specific isometric tasks, disease, muscle activation ($EMG$) and subacromial narrowing. There are also some weaknesses of our study that need to be taken into account when interpreting our results. Firstly, there was an age difference between patients with RC tears and the two other groups, due to the fact that impingement and RC tears have an age-dependent prevalence and the selected controls were relatively young. Nevertheless, it has been previously reported that adductor co-activation seems not to be age-dependent. Secondly, systematic measurement errors are common in AP shoulder radiographs. Patient positioning can greatly influence the projection of the subacromial space, with large projection and magnification errors leading to either over- or underestimating cranial translation of the humeral head. But earlier studies report that $AH$ measurements on AP radiographs are highly reproducible within and between investigators. In our study the patient setup was such to minimize repositioning for the three tasks and all the measurements were consistently applied in all groups, reducing potential projection and magnification errors. Thirdly, the subacromial volume (3-dimensional) may be more appropriate to assess the subacromial space compared to the $AH$ distance (2-dimensional). However, 3-dimensional volume measurements are elaborate, require 3-dimensional imaging and are not practical for clinical use, while it would only enlarge the resolution of the measured effects. Fourthly, although applying isometric arm tasks in a similar position for all subjects (without gravity affecting the abduction-adduction comparison) is a strong point, we did not investigate subacromial narrowing at higher elevation angles unlike others. Lastly, the
referential ‘rest’ condition is not a fully relaxed position as the arm is rotated in external rotation, which might mask an actually larger humeral translation during abduction and adduction.

5. Conclusions

The results of our study show that in patients with RC tears, the subacromial space as measured on radiographs is generally narrower than in controls and patients with SIS and that all three subjects groups demonstrate similar absolute amounts of cranial humerus translation during active isometric abduction and adduction tasks. Muscle activation at rest was relatively high in the two RC disease groups and there appeared to be more adductor co-activation in patients (n.s.). We did not find an association between muscle activation of the Deltoid and main adductors and cranial humerus translation. Future studies assessing the relation between muscle activation and subacromial space should take into account e.g. muscle volume and degradation status to make more accurate estimations of muscle force, or use interventions such as nerve-blocks or a subacromial injection with anesthetics to realize changes in muscle activation within subjects and assess how this influences subacromial space.

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References


