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

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**ABSTRACT**

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

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

**Findings:** In the massive rotator cuff-tear group, we found reduced glenohumeral elevation compared to the subacromial pain syndrome (16°, 95% CI [10.5, 21.2], p < 0.001) and the isolated supraspinatus tear group (10°, 95% CI [4.0, 16.7], p = 0.002). Reduced glenohumeral elevation in massive rotator cuff tears coincides with an increase in scapulothoracic lateral rotation compared to subacromial pain syndrome (11°, 95% CI [6.5, 15.2], p < 0.001) and supraspinatus tears (7°, 95% CI [1.8, 12.1], p = 0.012). Comparable differences were observed for forward flexion. No differences in glenohumeral elevation were found between the subacromial pain syndrome and isolated supraspinatus tear group during arm elevation.

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

1. Introduction

Shoulder pain is the most prevalent cause for musculoskeletal upper arm function during activities of daily living and work (Linsell et al., 2006; Picavet and Schouten, 2003). Most shoulder complaints are attributed to pathologic changes in the rotator cuff (RC) (van der Windt et al., 1995). Main clinical entities of RC-disease comprise subacromial pain syndrome (SAPS) and RC-tears (Diercks et al., 2014; van der Windt et al., 1995). The latter is clinically divided for prognostic and therapeutic purposes in isolated supraspinatus tears and massive RC-tears, in which the supraspinatus tear usually extends toward the infraspinatus tendon (i.e. massive posterosuperior RC-tear) (Bedi et al., 2010).

The RC provides essential forces to minimize glenohumeral (GH) translations (i.e. stability) and torques for shoulder motion (Steenbrink et al., 2009; Veeger and van der Helm, 2007). A disturbed equilibrium of RC forces in RC-tears may endanger shoulder stability. Computer and
cadaver simulations have shown the negative impact of RC-tears involving the supraspinatus and infraspinatus muscle (i.e. massive posterosuperior RC-tears) on joint reaction forces and GH joint stability (Burkhart, 1992; Hansen et al., 2008; Magehrns et al., 2004a; Parsons et al., 2002; Steenbrink et al., 2009; Thompson et al., 1996). Clinically, lost GH stability is marked by excessive proximal migration of the humeral head (Henseler et al., 2015). Whereas proximal migration and range of motion are clinically used for diagnostic purposes to diagnose a patient with an RC-tear, the coordination of shoulder motion is generally not assessed. Knowledge on how the extent of an RC-tear affects the coordination of shoulder motion may provide additional diagnostic information. Some research has been done to study kinematics in RC-tears (Mell et al., 2005; Scibek et al., 2008), but those studies do not take into account the effect of tear size when evaluating kinematics. In addition, patients with massive posterosuperior RC-tears have not been extensively studied in 3D motion analyses (Ohl et al., 2011). Consequently, the link between increasing RC-tear size, with a subsequent reduction of infraspinatus forces, and in-vivo shoulder kinematics has still to be determined in order to support experimental findings in simulated RC-tears (McCully et al., 2006).

GH stability and mobility in massive RC-tears may require different kinematics in contrast to the other two clinical subgroups (Steenbrink et al., 2009). GH joint stability may improve by reduced scapular lateral rotation (i.e. increased GH elevation) when the force vector will be directed more toward the center of the glenoid, whereas mobility may improve by increased scapular lateral rotation (i.e. reduced GH elevation) as a result of deltoid lengthening (Klein Breteler et al., 1999; Steenbrink et al., 2006; Steenbrink et al., 2009).

The aim of our study was to study the effect of RC-tears and its size on shoulder kinematics by comparing three clinically distinct groups with RC related pain: SAPS (i.e. excluding full-thickness RC-tears (Diercks et al., 2014)), isolated supraspinatus tears and massive posterosuperior RC-tears. We asked: (1) Do patients with massive posterosuperior RC tears exhibit reduced glenohumeral elevation compared to patients with an intact RC (i.e. SAPS) or isolated supraspinatus tear? (2) Is scapulothoracic lateral rotation dissimilar between patients with subacromial pain syndrome (SAPS, i.e. intact RC), an isolated supraspinatus tear or a massive RC tear? We hypothesized that patients with a massive posterosuperior RC-tear would have a reduced contribution of GH elevation (i.e. increased scapular lateral rotation) to the overall elevation compared to patients with SAPS or an isolated tear of the supraspinatus.

2. Methods

2.1. Participants

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

Group I consisted of thirty-four patients with subacromial pain syndrome (SAPS) with an MR proven intact RC, who were recruited at the outpatient clinic of three regional hospitals (Leiden University Medical Center, Medical Center Haaglanden and Alrijne Hospital) (Diercks et al., 2014). SAPS was clinically defined by a positive Hawkins and Neer impingement test in combination with at least one of the following clinical signs of SAPS: pain during shoulder movements, pain at night or incapable of lying on the shoulder, painful arc, diffuse pain at palpation of the greater tuberosity, scapular dyskinesia, a positive full/empty can test or a positive Yocum test. Only patients aged between 35 and 60 years with unilateral shoulder complaints for at least 3 months were included. Exclusion criteria were insufficient Dutch language skills, prior shoulder surgery, shoulder fracture or dislocation, radiocapitulopathy, frozen shoulder, electronic implants, (inflammatory) GH or symptomatic acromioclavicular osteoarthritis, calcific tendinitis, full-thickness RC-tear, PASTA lesion, labrum or ligament pathology, pulley lesion, biceps tendinopathy, os acromiale and tumor.

Group II consisted of twenty-one patients with an isolated full-thickness and degenerative supraspinatus tear who were included at the Medical Center Haaglanden when suffering from impaired function and pain (i.e. Davidson type I or II) (Davidson et al., 2005). All patients were scheduled for surgical RC repair and the extent of RC-tears was intra-operatively confirmed.

Group III consisted of fifty-four patients with a massive posterosuperior RC-tear recruited at two hospitals (Leiden University Medical Center and Medical Center Haaglanden). A massive posterosuperior RC-tear was defined according to the criteria of Davidson et al. as type 3 full-thickness posterosuperior tear, with a tear width of ≥ 20 mm, a length of ≥ 20 mm, and partial or complete detachment of the infraspinatus insertion side (Davidson et al., 2005). The teres minor muscle was intact in all participants. Patients suffered from either pain or impaired shoulder function during activities of daily living.

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

Baseline characteristics are presented in Table 1. Patients may have participated in earlier studies (de Witte et al., 2013; Kolk et al., 2015, 2016; Steenbrink et al., 2006; Steenbrink et al., 2010a; Steenbrink et al., 2010b). The medical ethics committees of Leiden University Medical Center (P07.123 & P09.227) and Zuidwest Holland (P07.116) approved all examinations. Written informed consent was obtained from all participants.

2.2. Measurement set-up

Kinematics in affected shoulders were evaluated in a standardized seated position with the Flock of Birds (FoB) 3D electromagnetic tracking system (Ascension Technology Inc., Milton, Vermont, USA). An extended range transmitter generated an electromagnetic field to record the position and orientation of seven wired sensors at about 30 Hz in order to examine bilateral shoulder motion with six degrees of freedom. Motion of the shoulder girdle was recorded with three wired sensors attached to both arms. One sensor was adhered to the flat cranio-lateral surface of the acromion with self-adhesive tape. Other sensors were attached to the flat surface of the distal humerus and the dorsal side of the distal forearm with a Velcro strap. The seventh sensor was attached to the manubrium sterni with self-adhesive tape. Subsequently, twenty-four bony landmarks were manually palpated and digitized as recommended by the International Society of

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>SAPS (n = 34)</th>
<th>Supraspinatus tear (n = 21)</th>
<th>Massive RC-tear (n = 54)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yrs., SD)</td>
<td>50 (6)</td>
<td>58 (9)</td>
<td>61 (7)</td>
</tr>
<tr>
<td>Female (n, %)</td>
<td>19 (56)</td>
<td>12 (57)</td>
<td>20 (37)</td>
</tr>
<tr>
<td>Left side affected, (n, %)</td>
<td>14 (41)</td>
<td>10 (48)</td>
<td>19 (35)</td>
</tr>
<tr>
<td>Dominant side affected (n, %)</td>
<td>21 (62)</td>
<td>11 (52)</td>
<td>35 (65)</td>
</tr>
<tr>
<td>VAS for pain during movement (mm, SD)</td>
<td>39 (24)</td>
<td>59 (31)</td>
<td>47 (27)</td>
</tr>
</tbody>
</table>
Biomechanics (ISB) (Wu et al., 2005). Digitization of bony landmarks is accomplished by calculating the coordinates of bony landmark using position and orientation of a sensor mounted on a stylus (Meskers et al., 1999). All methodology has been validated earlier (de Groot, 1997; Jordan et al., 2000; Meskers et al., 1998; Meskers et al., 1999; Meskers et al., 2007; Milne et al., 1996). We visualized the places of sensors in Supplement 1, landmarks were digitized according to the ISB guidelines (Wu et al., 2005).

2.3. Measurements

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

2.4. Data processing

Bony landmarks were used to reconstruct a local Cartesian right-handed coordinate system for the thorax, scapula and humerus according to the ISB recommendations (Wu et al., 2005). Left segments were mirrored to the right. Local coordinate systems consisted of axis pointing anteriorly (X), superiorly (Y) and laterally to the right (Z).

Humerothoracic motion, ST motion and GH motion were calculated according to the appropriate Euler or Cardan sequence (Wu et al., 2005). For humerothoracic and GH motion an Euler sequence (Y-X-Y) was applied: 1) plane of elevation is rotation around the thoracic Y-axis, 0° represents elevation in the frontal plane and 90° elevation in the parasagittal plane; 2) elevation is negative rotation around the rotated humeral X-axis; 3) internal rotation is positive rotation around the rotated humeral Y-axis. GH motion was described as follows: 1) GH plane of elevation is rotation around the scapular Y-axis; 2) GH elevation is negative rotation around the humeral X-axis; 3) internal GH rotation is positive rotation around the longitudinal humeral Y-axis. For ST motion a fixed Cardan sequence (Y-X-Z) was applied: 1) protraction (i.e. internal rotation) is positive rotation around the thoracic Y-axis; 2) lateral rotation (i.e. upward rotation) is negative rotation around the scapular X-axis; 3) posterior tilt is positive rotation around the scapular Z-axis. In contrast to Wu et al., we expressed these rotations as a covariate (Graichen et al., 1999a; Ludewig et al., 2009). In our secondary analysis, we also adjusted for age, sex and whether the dominant shoulder was involved. Mean difference between the RC pathologies in GH and ST orientation were calculated at each humerothoracic elevation angle. IBM SPSS statistics for Windows version 20.0 (IBM Corp, 2011, Armonk, New York, USA) was used. A 2-sided p-value of < 0.05 was considered statistically significant.

3. Results

3.1. Humerus range of motion (RoM)

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

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

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

Fig. 2. Glenohumeral rotations. Glenohumeral motion (± standard error) from the initial position at 20–30° of humerothoracic elevation in patients with SAPS (straight line), an isolated supraspinatus RC-tear (dashed line) and a massive posterosuperior RC-tear (small-dashed line) during abduction (panel A) and forward flexion (panel B). Mean initial positions are described for SAPS (△), isolated supraspinatus tears (■), and massive RC-tears (▽) at the left. Patients with a massive posterosuperior RC-tear demonstrated significantly less glenohumeral elevation compared to SAPS (*) and isolated supraspinatus tears (+).
humeral axial rotation were investigated as group, respectively (Table 3). More lateral rotation was found during and 2° to 7° more lateral rotation in the massive posterosuperior RC-tear (Fig. 3A and B). From 30° to 110° of abduction, there was 2° to 11° SAPS, an isolated supraspinatus tear or a massive RC tear?

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

Patients with a massive posterosuperior RC-tear revealed significantly more ST lateral rotation (i.e. upward rotation) compared to the other shoulder conditions for both abduction and forward flexion (Fig. 3A and B). From 30° to 110° of abduction, there was 2° to 11° and 2° to 7° more lateral rotation in the massive posterosuperior RC-tear group compared to the SAPS group and isolated supraspinatus tear group, respectively (Table 3). More lateral rotation was found during forward flexion compared to the SAPS group (i.e. 3° to 9°) and supraspinatus tear group (e.g. 4° at 70–80°) (Table 3). Patients with an isolated supraspinatus tear had more lateral rotation during forward flexion from 80° to 110° elevation (i.e. 4° to 6°) compared to patients with SAPS (Table 3).

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

### 4. Discussion and conclusions

In the present study we aimed to differentiate kinematics between three distinct RC diseases in order to improve the understanding of shoulder kinematics in patients with symptomatic RC-disease. Patients with a massive posterosuperior RC-tear showed less GH elevation during arm elevation compared to patients with SAPS or isolated supraspinatus tears. The SAPS and isolated supraspinatus tear groups did not differ with respect to GH elevation. Reduced GH elevation in massive posterosuperior RC-tears is accompanied by a marked increase in ST lateral rotation.
Our study supports the findings in simulated massive posterosuperior RC-tears created after a suprascapular nerve block in healthy volunteers (McCully et al., 2006). McCully et al. showed a decline in GH elevation and increase in ST lateral rotation in simulated massive posterosuperior RC-tears (McCully et al., 2006). Since the infraspinatus muscle has a direct impact on the GH joint and does not directly control ST motion, McCully et al. concluded that an increase in ST lateral rotation should be compensatory in nature (McCully et al., 2006). In line with most kinematic evaluations we observed small differences in GH and ST motion between isolated supraspinatus tears and patients with SAPS (Deutsch et al., 1996; Graichen et al., 2001; Mell et al., 2005; Paletta et al., 1997; Yamaguchi et al., 2000). In the literature, no differences in shoulder kinematics were previously found in patients with a massive RC-tear compared to healthy volunteers (Ohl et al., 2015). Most studies investigated kinematics in groups without categorizing the type of RC-tear, causing heterogeneity (Deutsch et al., 1996; Mell et al., 2005; Ohl et al., 2015; Paletta et al., 1997). Heterogeneity might result in additional variance, a lower statistical power, and consequently might lead to other conclusions (Deutsch et al., 1996; Mell et al., 2005; Ohl et al., 2015; Paletta et al., 1997). As an alternative, we proposed to stratify patients according to diagnostic subgroups based on our biomechanical rationale (Steenbrink et al., 2009). Importantly, findings suggest that physicians may discriminate massive RC-tears from less extensive RC-tears by observing coordination of shoulder motion, making kinematic analysis a possible future diagnostic tool.

We observed the least amount of ST lateral rotation and greater GH elevation in patients with SAPS, which was also expected based on our...
biomechanical hypothesis. Conflicting results have been reported for ST kinematics in patients with SAPS and in subjects without shoulder pain has been shown to be dissimilar (Endo et al., 2001; Graichen et al., 1999b; Lawrence et al., 2014; Ludewig and Cook, 2000; Ludewig and Reynolds, 2009; Lukasiewicz et al., 1999; McClure et al., 2006). A major strength of our study was that we evaluated the condition of the RC using MR imaging, and confirmed that the RC was intact in all SAPS patients. Since physical examination alone lacks accuracy to correctly identify RC-tears and RC-tear may adversely affect shoulder kinematics, we consider imaging of the RC crucial to reveal the presence of RC-tears in this kinematic study, (Park et al., 2005). Though, subjects with SAPS might exhibit pathologic kinematics as well, even with the RC being intact. Those differences in kinematics between SAPS patients and asymptomatic individuals are still unclear and need further research (Endo et al., 2001; Graichen et al., 2001; Lawrence et al., 2014; Ludewig and Cook, 2000; Ludewig and Reynolds, 2009; Lukasiewicz et al., 1999; McClure et al., 2006).

4.2. A biomechanical perspective

Earlier in silico and cadaver studies have shown a substantial increase in forces generated by the posterior RC (i.e. residual infraspinatus or teres minor) to maintain a congruent articulation of the GH joint in RC-tears (Hansen et al., 2008; Howell et al., 1986; Magermans et al., 2004b; Parsons et al., 2002; Steenbrink et al., 2009; Thompson et al., 1996). The infraspinatus, teres minor and subscapularis muscles prevent excessive proximal migration of the humeral head in isolated supraspinatus tears (Burkhart, 1992; Hansen et al., 2008; Inman et al., 1944; Magermans et al., 2004b; Parsons et al., 2002; Steenbrink et al., 2009; Thompson et al., 1996). If an RC-tear extends beyond the supraspinatus into the infraspinatus muscle, the teres minor is suggested to become hypertrophic to compensate for the loss of stabilizing infraspinatus forces (Kikukawa et al., 2014). Loss of glenohumeral elevation in massive RC-tears at equal arm position reflects a redistribution of muscle torques and thus altered coordination, since net arm
torque remains similar. In massive RC-tears, the deltoid muscle compensates for lost RC-torques during elevation of the arm (Steinbrink et al., 2009; Steinbrink et al., 2010a). As a compensation strategy, strengthening of the deltoid seems favorable to generate sufficient torques for arm elevation (Klein Breteler et al., 1999). When increasing relative scapula lateral rotation at equal total arm abduction (i.e. abduction movement of the scapula relative to the humerus), the length of the deltoid muscle may increase toward its optimal length (Klein Breteler et al., 1999), optimizing abduction moment capacity. The latter might be an explanation for our findings. Also co-activation of the latissimus dorsi or teres major might compromise GH elevation in massive posterosuperior RC-tears. Co-activation of shoulder adductors was postulated to prevent proximal migration of the humerus (Steinbrink et al., 2006; Steinbrink et al., 2010a; Steinbrink et al., 2010b). Nevertheless, the exact biomechanics that contribute to our in vivo observations are not yet fully understood.

4.3. Limitations and future work

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

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

4.4. Conclusion and relevance

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

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.clinbiomech.2017.03.014.

Conflict of interest
None.

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