Clinical Biomechanics 45 (2017) 43–51

Contents lists available at ScienceDirect

Clinical Biomechanics

journal homepage: www.elsevier.com/locate/clinbiomech

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

Arjen Kolk[a,b], Jan Ferdinand Henseler[a,b], Pieter Bas de Witte[a], Erik W. van Zwet[c], Peer van der Zwaal[d], Cornelis P.J. Visser[e], Jochem Nagels[a], Rob G.H.H. Nelissen[a], Jurriaan H. de Groot[b,*]

[a] Department of Orthopaedics, Leiden University Medical Center, Postzone J-11-R, PO Box 9600, 2300RC Leiden, the Netherlands
[b] Laboratory for Kinematics and Neuromechanics, Department of Orthopaedics and Rehabilitation, Leiden University Medical Center, Postzone J-11-R, PO Box 9600, 2300RC Leiden, the Netherlands
[c] Department of Medical Statistics and Bioinformatics, Leiden University Medical Center, Postzone S5-P, PO Box 9600, 2300RC Leiden, the Netherlands
[d] Department of Orthopaedic Surgery, Medical Center Haaglanden-Bronovo, Bronovolaan 5, 2597AX The Hague, the Netherlands
[e] Department of Orthopaedics, Alrijne Hospital, Postzone RZL-22, Simon Smitweg 1, 2353GA Leiderdorp, the Netherlands

ARTICLE INFO

Keywords:
Rotator cuff
Shoulder
Kinematics
Tears
Movement
Pain
Kinesiology

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], $p = 0.002$) at 110° abduction. Reduced glenohumeral elevation in massive rotator cuff tears coincides with an increase in scapulothoracic lateral rotation compared to subacromial pain syndrome (11°, 95% 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 extremity complaints within our society, and coincides with reduced 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

* Corresponding author at: Laboratory for kinematics and Neuromechanics, Leiden University Medical Center (LUMC), Postzone J11R, PO Box 9600, 2300RC Leiden, the Netherlands.
E-mail addresses: a.kolk@lumc.nl (A. Kolk), J.F.Henseler@lumc.nl (J.F. Henseler), P.B.de_Witte@lumc.nl (P.B. de Witte), E.W.van_Zwet@lumc.nl (E.W. van Zwet), p.van.der.zwaal@mchaaglanden.nl (P. van der Zwaal), C.Visser@rijnland.nl (C.P.J. Visser), J.Nagels@lumc.nl (J. Nagels), R.G.H.H.Nelissen@lumc.nl (R.G.H.H. Nelissen), J.H.de_Groot@lumc.nl (J.H. de Groot).

http://dx.doi.org/10.1016/j.clinbiomech.2017.03.014
Received 8 September 2016; Accepted 28 March 2017
0268-0033/

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; Magermans 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., 2015). 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 dyskinesis, a positive full/empty can test or a positive Yocum test. Only patients aged between 35 and 60 years with unilateral shoulder complaints for at least 3 months were included. Exclusion criteria were insufficient Dutch language skills, prior shoulder surgery, shoulder fracture or dislocation, radiculopathy, frozen shoulder, electronic implants, (inflammatory) GH or symptomatic acromioclavicular osteoarthritis, calcific tendinitis, full-thickness RC-tear, PASTA lesion, labrum or ligament pathology, pulley lesion, biceps tendinopathy, os acromiale and 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, radiculopathy, 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 sternii with self-adhesive tape. Subsequently, twenty-four bony landmarks were manually palpated and digitized as recommended by the International Society of

Table 1
Baseline characteristics.

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

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_t), superiorly (Y_t) and laterally to the right (Z_t). Humerothoracic motion, ST motion and GH motion were calculated according to the appropriate Euler or Cardan sequence (Wu et al., 2005).

For humerothoracic and GH motion an Euler sequence (Y-X-Y) was applied in a moving system. Humerothoracic motion was described as follows: 1) plane of elevation is rotation around the thoracic Y-axis, 0° represents elevation in the frontal plane and 90° elevation in the parasagittal plane; 2) elevation is negative rotation around the rotated humeral X′-axis; 3) internal rotation is positive rotation around the rotated humeral Y″-axis. GH motion was described as follows: 1) GH plane of elevation is rotation around the scapular Y-axis; 2) GH elevation is negative rotation around the humeral X′-axis; 3) internal GH rotation is positive rotation around the longitudinal humeral Y″-axis. For ST motion a fixed Cardan sequence (Y-X-Z) was applied: 1) 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 humerothoracic elevation, ST lateral rotation and GH elevation as positive motion (Wu et al., 2005). Custom made MATLAB 2013b (The MathWorks Inc., Natick, Massachusetts, USA) software was used for data processing.

3D shoulder kinematics were calculated during arm abduction and forward flexion and an average of repeated movements was used. ST and GH motion were recorded up to 110° of humerothoracic elevation since accuracy of the acromion sensor decreases at higher elevation as a consequence of skin movement artifacts (Karduna et al., 2001). Data obtained during abduction (i.e. plane of elevation $< 30°$) and forward flexion (i.e. plane of elevation $> 45°$) were assessed for out of plane movements, data within the plane of interest qualified for our analysis. A mean position for ST and GH motion was interpolated for nine intervals of 10° humerothoracic elevation within the range of 20°–110°. Since we report on the motion starting from the initial position at 20–30°, we subtracted the initial mean GH or ST angle at 20–30° (i.e. offset) from successive angles and evaluated shoulder kinematics within the range of 30°–110° of humerothoracic elevation. Missing data, due to an inability to raise the arm up to 110°, related to our dependent variable (Supplement 2). Hence, we conducted a stratified analysis using data of all patients and an analysis using data from a subgroup of patients who was able to fully raise their arm up to 110°. Since conclusions based on both analyses with respect to GH (Supplement 3) and ST (Supplement 4) kinematics were comparable, we present our analysis using all patients. From the 109 patients, abduction and forward flexion were $< 30°$ in 6 and 8 patients, respectively. The numbers of patients with missing data are described within the supplements.

2.5. Statistical analysis

We conducted one-way ANOVAs to compare maximal humerothoracic RoM between three RC pathologies. To account for unequal variance between the groups, we used Welch F tests. In case of significance, we used Games-Howell post-hoc tests to assess the differences. ST and GH rotations were compared between the three RC pathologies with a linear mixed model. Mixed model analysis is a regression model that deals with correlated errors between various intervals while moving the arm (i.e. repeated measures) using a correlation matrix (Verbeke and Molenberghs, 2009). An autoregressive covariance structure of order one with heterogeneous variances was used (Verbeke and Molenberghs, 2009). The dependent variable was a single ST or GH rotation. In our primary analysis, we investigated humerothoracic elevation interval and the interaction between RC pathology and humerothoracic elevation interval as fixed effects. The repeated factor was the humerothoracic elevation interval. Shoulder movements were unconstrained because guided movements do not represent daily life motion. Consequently, slight differences in plane of elevation and axial humeral rotation between subjects occurred. Since out of plane elevation and axial humeral rotation may affect shoulder kinematics, we adjusted for humerothoracic rotations by including these rotations as a covariate (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)

Humerothoraric abduction and forward flexion were lower in the massive posterosuperior RC-tear group compared to SAPS (Fig. 1).

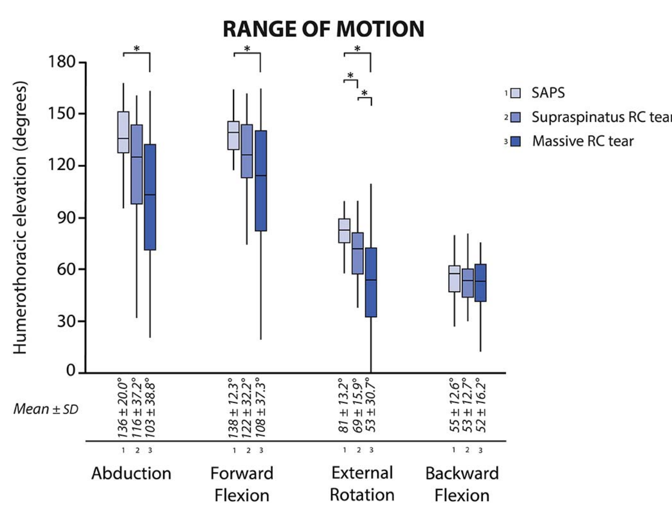

Fig. 1. Range of motion.Boxplots show the maximal humerothoracic ROM with the median, interquartile range and range in patients with SAPS (N = 34), a supraspinatus RC-tear (N = 21) and a massive posterosuperior RC-tear (N = 54). *Significant set at $p < 0.05$.

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).

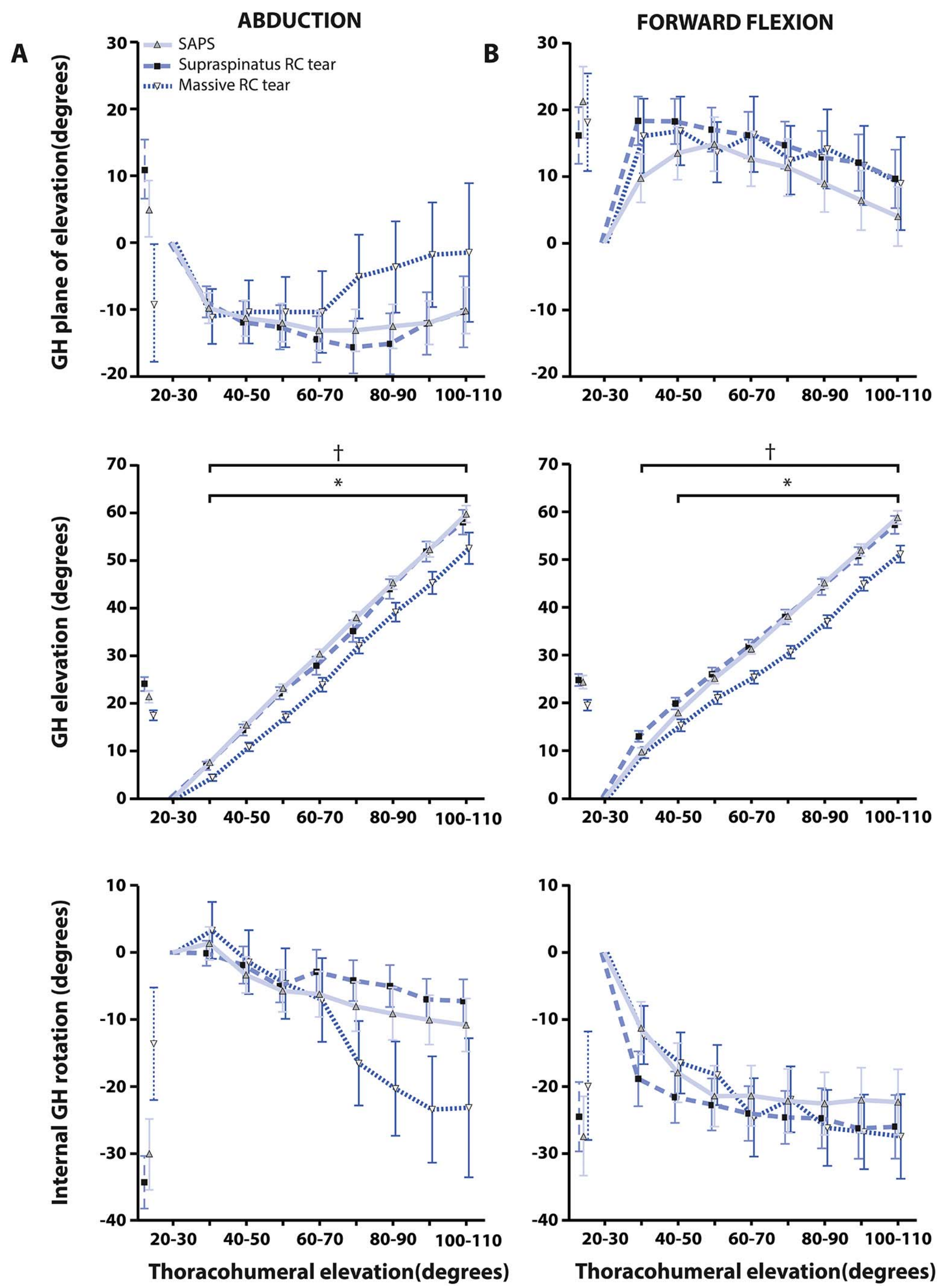

Fig. 2. Glenohumeral rotations.Glenohumeral motion (± standard error) from the initial position at 20–30°of humerothoracic elevation in patients with SAPS (straight line), an isolated supraspinatus RC-tear (dashed line) and a massive posterosuperior RC-tear (small-dashed line) during abduction (panel 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 (†).

Table 2
Difference in glenohumeral elevation.

Abduction		Massive RC-tear (n = 48) vs. SAPS (n = 34)		Massive RC-tear (n = 48) vs. Supraspinatus tear (n = 21)		SAPS (n = 34) vs. Supraspinatus tear (n = 21)	
		Mean difference (°, 95% CI)	p-Value	Mean difference (°, 95% CI)	p-Value	Mean difference (°, 95% CI)	p-Value
30–40°	a	3 [1.5, 5.4]	0.001*	3 [0.9, 5.4]	0.008*	− 0 [− 2.7, 2.1]	0.806
	b	3 [1.2, 5.6]	0.003*	3 [0.6, 5.4]	0.014*	− 0 [− 3.0, 2.2]	0.749
40–50°	a	6 [2.9, 8.6]	< 0.001*	4 [1.1, 7.7]	0.010*	− 1 [− 4.9, 2.1]	0.442
	b	6 [2.7, 8.8]	< 0.001*	4 [0.8, 7.7]	0.015*	− 1 [− 5.1, 2.2]	0.417
50–60°	a	8 [4.7, 11.3]	< 0.001*	6 [2.1, 9.8]	0.003*	− 2 [− 6.1, 2.0]	0.317
	b	8 [4.5, 11.4]	< 0.001*	6 [1.8, 9.8]	0.004*	− 2 [− 6.4, 2.0]	0.303
60–70°	a	10 [5.7, 13.3]	< 0.001*	6 [1.4, 10.4]	0.010*	− 4 [− 8.3–1.1]	0.130
	b	10 [5.5, 13.5]	< 0.001*	6 [1.1, 10.4]	0.015*	− 4 [− 8.7, 1.1]	0.129
70–80°	a	11 [7.3, 15.4]	< 0.001*	7 [2.2, 11.8]	0.005*	− 4 [− 9.4, 0.7]	0.092
	b	11 [7.1, 15.6]	< 0.001*	7 [2.0, 11.8]	0.007*	− 4 [− 9.7, 0.7]	0.091
80–90°	a	13 [8.3, 17.1]	< 0.001*	8 [3.1, 13.4]	0.002*	− 4 [− 9.8, 1.0]	0.109
	b	13 [8.1, 17.3]	< 0.001*	8 [2.8, 13.5]	0.003*	− 4 [− 10.2, 1.0]	0.108
90–100°	a	14 [9.5, 19.1]	< 0.001*	10 [3.9, 15.3]	0.001*	− 5 [− 10.6, 1.2]	0.114
	b	14 [9.4, 19.4]	< 0.001*	9 [3.6, 15.3]	0.002*	− 5 [− 10.9, 1.2]	0.112
100–110°	a	16 [9.5, 19.1]	< 0.001*	10 [4.0, 16.7]	0.002*	− 6 [− 12.1, 0.9]	0.092
	b	16 [10.4, 21.5]	< 0.001*	10 [3.7, 16.7]	0.002*	− 6 [− 12.5, 0.9]	0.090

Forward flexion		Massive RC-tear (n = 48) vs. SAPS (n = 33)		Massive RC-tear (n = 48) vs. Supraspinatus tear (n = 20)		SAPS (n = 33) vs. Supraspinatus tear (n = 20)	
		Mean difference (°, 95% CI)	p-Value	Mean difference (°, 95% CI)	p-Value	Mean difference (°, 95% CI)	p-Value
30–40°	a	2 [− 1.3, 4.9]	0.247	4 [0.7, 7.9]	0.021*	2 [− 1.4, 6.3]	0.205
	b	3 [− 0.4, 7.0]	0.084	4 [0.7, 8.2]	0.021*	1 [− 3.1, 5.3]	0.591
40–50°	a	4 [0.2, 7.0]	0.036*	5 [1.5, 9.5]	0.007*	2 [− 2.4, 6.1]	0.385
	b	5 [1.1, 9.0]	0.012*	6 [1.5, 9.6]	0.007*	1 [− 4.0, 5.1]	0.825
50–60°	a	5 [1.5, 8.7]	0.005*	6 [2.1, 10.5]	0.004*	1 [− 3.3, 5.6]	0.605
	b	7 [2.5, 10.7]	0.002*	6 [2.1, 10.7]	0.004*	− 0 [− 5.0, 4.6]	0.938
60–70°	a	6 [2.2, 9.3]	0.002*	6 [2.2, 10.6]	0.003*	1 [− 3.7, 5.1]	0.754
	b	7 [3.1, 11.3]	0.001*	7 [2.3, 10.8]	0.003*	− 1 [− 5.4, 4.1]	0.784
70–80°	a	8 [4.3, 11.9]	< 0.001*	8 [3.8, 12.7]	< 0.001*	0 [− 4.6, 4.8]	0.960
	b	10 [5.3, 13.9]	< 0.001*	8 [3.8, 12.9]	< 0.001*	− 1 [− 6.2, 3.8]	0.624
80–90°	a	9 [5.6, 13.2]	< 0.001*	9 [4.3, 13.2]	< 0.001*	− 1 [− 5.4, 4.0]	0.770
	b	11 [6.5, 15.1]	< 0.001*	9 [4.3, 13.3]	< 0.001*	− 2 [− 7.0, 2.9]	0.416
90–100°	a	10 [6.2, 14.3]	< 0.001*	9 [3.8, 13.4]	0.001*	− 2 [− 6.7, 3.4]	0.523
	b	12 [7.2, 16.3]	< 0.001*	9 [3.9, 13.6]	0.001*	− 3 [− 8.3, 2.3]	0.267
100–110°	a	12 [7.1, 16.1]	< 0.001*	10 [4.3, 14.9]	0.001*	− 2 [− 7.6, 3.6]	0.475
	b	13 [8.1, 18.0]	< 0.001*	10 [4.4, 15.1]	0.001*	− 3 [− 9.2, 2.4]	0.252

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

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

* Statistically significant difference at $p < 0.05$.

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

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

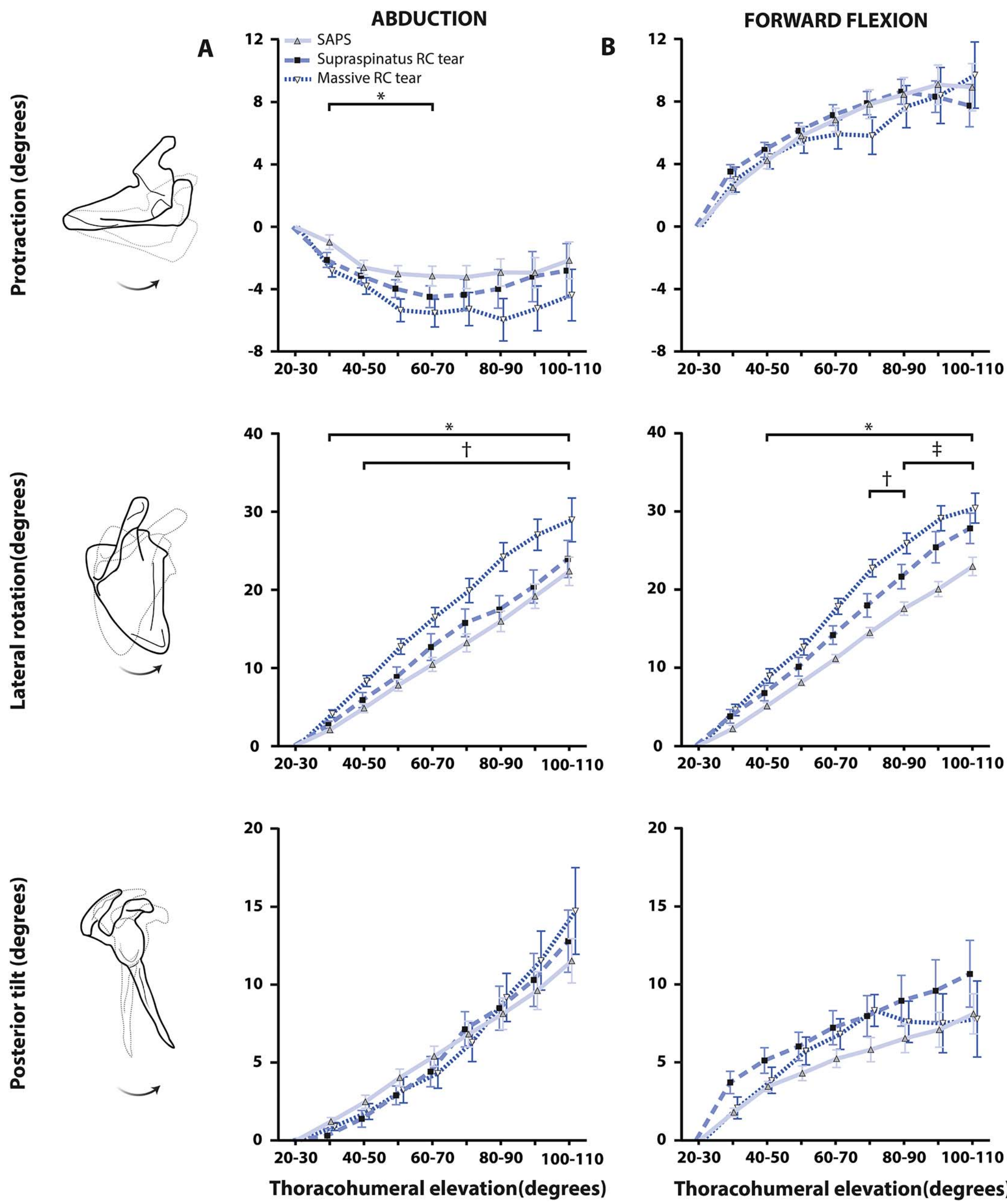

Fig. 3. Scapulothoracic rotations.Scapulothoracic motion (± standard error) from the initial position at 20–30°of humerothoracic elevation in patients with SAPS (straight line), a supraspinatus RC-tear (dashed line) and a massive posterosuperior RC-tear (small-dashed line) during abduction (panel A)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

4.1. Kinematics in patients

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

Table 3
Difference in scapulothoracic lateral rotation.

Abduction

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

Forward flexion

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

[a] Mixed model analysis: Humerothoracic elevation angle, RC pathology (i.e. SAPS, supraspinatus tear or massive RC-tear) × humerothoracic elevation angle, plane of elevation and humeral axial rotation were investigated as fixed effects.
[b] Mixed model analysis (adjusted for age, sex and hand dominancy): Humerothoracic elevation angle, RC pathology (i.e. SAPS, supraspinatus tear or massive RC-tear) × humerothoracic elevation angle, plane of elevation, humeral axial rotation, age, sex (male or female) and dominant shoulder affected (yes or no) were investigated as fixed effects.
* Statistically significant difference at $p < 0.05$.

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 (Steenbrink et al., 2009; Steenbrink et al., 2010a). As a compensation strategy, lengthening 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. adduction 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 (Steenbrink et al., 2006; Steenbrink et al., 2010a; Steenbrink 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 estimations 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.

Acknowledgements

We thank Frans Steenbrink for conducting a noteworthy part of the measurements. This work was supported by the Dutch Arthritis Foundation [grant number 13-1-303]. The funding organization had no direct role in the design or conduct of this study; collection, management, analysis, and the interpretation of the data; preparation, review, or approval of the manuscript; and the decision to submit the manuscript for publication.

References

Bedi, A., Dines, J., Warren, R.F., Dines, D.M., 2010. Massive tears of the rotator cuff. J. Bone Joint Surg. Am. 92, 1894–1908. http://dx.doi.org/10.2106/JBJS.I.01531.

Burkhart, S.S., 1992. Fluoroscopic comparison of kinematic patterns in massive rotator cuff tears. A suspension bridge model. Clin. Orthop. Relat. Res. 144–152.

Davidson, J.F., Burkhart, S.S., Richards, D.P., Campbell, S.E., 2005. Use of preoperative magnetic resonance imaging to predict rotator cuff tear pattern and method of repair. Arthroscopy 21, 1428. http://dx.doi.org/10.1016/j.arthro.2005.09.015.

Deutsch, A., Altchek, D.W., Schwartz, E., Otis, J.C., Warren, R.F., 1996. Radiologic measurement of superior displacement of the humeral head in the impingement syndrome. J. Shoulder Elb. Surg. 5, 186–193. http://dx.doi.org/10.1016/S1058-2746(05)80004-7.

Diercks, R., Bron, C., Dorrestijn, O., Meskers, C., Naber, R., de, R.T., Willems, J., Winters, J., van der Woude, H.J., 2014. Guideline for diagnosis and treatment of subacromial pain syndrome: a multidisciplinary review by the Dutch Orthopaedic Association. Acta Orthop. 85, 314–322. http://dx.doi.org/10.3109/17453674.2014.920991.

Endo, K., Ikata, T., Katoh, S., Takeda, Y., 2001. Radiographic assessment of scapular rotational tilt in chronic shoulder impingement syndrome. J. Orthop. Sci. 6, 3–10. http://dx.doi.org/10.1007/s007760170017.

Graichen, H., Bonel, H., Stammberger, T., Englmeier, K.H., Reiser, M., Eckstein, F., 1999a. Subacromial space width changes during abduction and rotation—a 3-D MR imaging study. Surg. Radiol. Anat. 21, 59–64. http://dx.doi.org/10.1007/BF01635055.

Graichen, H., Bonel, H., Stammberger, T., Haubner, M., Rohrer, H., Englmeier, K.H., Reiser, M., Eckstein, F., 1999b. Three-dimensional analysis of the width of the subacromial space in healthy subjects and patients with impingement syndrome. AJR Am. J. Roentgenol. 172, 1081–1086. http://dx.doi.org/10.2214/ajr.172.4.10587151.

Graichen, H., Stammberger, T., Bonel, H., Wiedemann, E., Englmeier, K.H., Reiser, M., Eckstein, F., 2001. Three-dimensional analysis of shoulder girdle and supraspinatus motion patterns in patients with impingement syndrome. J. Orthop. Res. 19, 1192–1198. http://dx.doi.org/10.1016/s0736-0266(01)00035-3.

de Groot, J.H., 1997. The variability of shoulder motions recorded by means of palpation. Clin. Biomech. 12, 461–472. http://dx.doi.org/10.1016/s0268-0033(97)00031-4.

Hansen, M.L., Otis, J.C., Johnson, J.S., Cordasco, F.A., Craig, E.V., Warren, R.F., 2008. Biomechanics of massive rotator cuff tears: implications for treatment. J. Bone Joint Surg. Am. 90, 316–325. http://dx.doi.org/10.2106/JBJS.F.00880.

Henseler, J.F., Raz, Y., Nagels, J., van Zwet, E.W., Raz, V., Nelissen, R.G., 2015. Multivariate analyses of rotator cuff pathologies in shoulder disability. PLoS One 10, e0118158. http://dx.doi.org/10.1371/journal.pone.0118158.

Howell, S.M., Imobersteg, A.M., Seger, D.H., Marone, P.J., 1986. Clarification of the role of the supraspinatus muscle in shoulder function. J. Bone Joint Surg. Am. 68, 398–404.

Inman, V.T., Saunders, J.R., Abbott, L.C., 1944. Observations on the function of the shoulder joint. J. Bone Joint Surg. 26, 1–30.

Jordan, K., Dziedzic, K., Jones, P.W., Ong, B.N., Dawes, P.T., 2000. The reliability of the three-dimensional FASTRAK measurement system in measuring cervical spine and shoulder range of motion in healthy subjects. Rheumatology (Oxford) 39, 382–388.

Karduna, A.R., McClure, P.W., Michener, L.A., Sennett, B., 2001. Dynamic measurements of three-dimensional scapular kinematics: a validation study. J. Biomech. Eng. 123, 184–190. http://dx.doi.org/10.1115/1.1351892.

Kikukawa, K., Ide, J., Kikuchi, K., Morita, M., Mizuta, H., Ogata, H., 2014. Hypertrophic changes of the teres minor muscle in rotator cuff tears: quantitative evaluation by magnetic resonance imaging. J. Shoulder Elb. Surg. 23, 1800–1805. http://dx.doi.org/10.1016/j.jse.2014.03.014.

Klein Breteler, M.D., Spoor, C.W., Van der Helm, F.C., 1999. Measuring muscle and joint geometry parameters of a shoulder for modeling purposes. J. Biomech. 32, 1191–1197. http://dx.doi.org/10.1016/S0021-9290(99)00122-0.

Kolk, A., De Witte, P.B., Henseler, J.F., Van Zwet, E.W., Van Arkel, E.R., Van der Zwaal, P., Nelissen, R.G., De Groot, J.H., 2015. Three-dimensional shoulder kinematics normalize after rotator cuff repair. J. Shoulder Elb. Surg.. http://dx.doi.org/10.1016/j.jse.2015.10.021. (Accepted for publication).

Kolk, A., Henseler, J.F., de Witte, P.B., van Arkel, E.R., Visser, C.P., Nagels, J., Nelissen, R.G., de Groot, J.H., 2016. Subacromial anaesthetics increase asymmetry of scapular kinematics in patients with subacromial pain syndrome. Man. Ther. 26, 31–37. http://dx.doi.org/10.1016/j.math.2016.07.002.

Lawrence, R.L., Braman, J.P., LaPrade, R.F., Ludewig, P.M., 2014. Comparison of 3-

dimensional shoulder complex kinematics in individuals with and without shoulder pain, part 1: sternoclavicular, acromioclavicular, and scapulothoracic joints. J. Orthop. Sports Phys. Ther. 44, 636–638. http://dx.doi.org/10.2519/jospt.2014.5339.

Linsell, L., Dawson, J., Zondervan, K., Rose, P., Randall, T., Fitzpatrick, R., Carr, A., 2006. Prevalence and incidence of adults consulting for shoulder conditions in UK primary care; patterns of diagnosis and referral. Rheumatology (Oxford) 45, 215–221. http://dx.doi.org/10.1093/rheumatology/kei139.

Ludewig, P.M., Cook, T.M., 2000. Alterations in shoulder kinematics and associated muscle activity in people with symptoms of shoulder impingement. Phys. Ther. 80, 276–291.

Ludewig, P.M., Reynolds, J.F., 2009. The association of scapular kinematics and glenohumeral joint pathologies. J. Orthop. Sports Phys. Ther. 39, 90–104. http://dx.doi.org/10.2519/jospt.2009.2808.

Ludewig, P.M., Phadke, V., Braman, J.P., Hassett, D.R., Cieminski, C.J., LaPrade, R.F., 2009. Motion of the shoulder complex during multiplanar humeral elevation. J. Bone Joint Surg. Am. 91, 378–389. http://dx.doi.org/10.2106/jbjs.g.01483.

Lukasiewicz, A.C., McClure, P., Michener, L., Pratt, N., Sennett, B., 1999. Comparison of 3-dimensional scapular position and orientation between subjects with and without shoulder impingement. J. Orthop. Sports Phys. Ther. 29, 574–583. http://dx.doi.org/10.2519/jospt.1999.29.10.574.

Magermans, D.J., Chadwick, E.K., Veeger, H.E., Rozing, P.M., van der Helm, F.C., 2004a. Effectiveness of tendon transfers for massive rotator cuff tears: a simulation study. Clin. Biomech. 19, 116–122. http://dx.doi.org/10.1016/j.clinbiomech.2003.09.008.

Magermans, D.J., Chadwick, E.K., Veeger, H.E., van der Helm, F.C., Rozing, P.M., 2004b. Biomechanical analysis of tendon transfers for massive rotator cuff tears. Clin. Biomech. 19, 350–357. http://dx.doi.org/10.1016/j.clinbiomech.2003.11.013.

McClure, P.W., Michener, L.A., Karduna, A.R., 2006. Shoulder function and 3-dimensional scapular kinematics in people with and without shoulder impingement syndrome. Phys. Ther. 86, 1075–1090.

McCully, S.P., Suprak, D.N., Kosek, P., Karduna, A.R., 2006. Suprascapular nerve block disrupts the normal pattern of scapular kinematics. Clin. Biomech. 21, 545–553. http://dx.doi.org/10.1016/j.clinbiomech.2006.02.001.

Mell, A.G., LaScalza, S., Guffey, P., Ray, J., Maciejewski, M., Carpenter, J.E., Hughes, R.E., 2005. Effect of rotator cuff pathology on shoulder rhythm. J. Shoulder Elb. Surg. 14, 58S–64S. http://dx.doi.org/10.1016/j.jse.2004.09.018.

Meskers, C.G., van der Helm, F.C., Rozendaal, L.A., Rozing, P.M., 1998. In vivo estimation of the glenohumeral joint rotation center from scapular bony landmarks by linear regression. J. Biomech. 31, 93–96. http://dx.doi.org/10.1016/s0021-9290(97)00101-2.

Meskers, C.G., Fraterman, H., van der Helm, F.C., Vermeulen, H.M., Rozing, P.M., 1999. Calibration of the "Flock of Birds" electromagnetic tracking device and its application in shoulder motion studies. J. Biomech. 32, 629–633. http://dx.doi.org/10.1016/s0021-9290(99)00011-1.

Meskers, C.G., van de Sande, M.A., de Groot, J.H., 2007. Comparison between tripod and skin-fixed recording of scapular motion. J. Biomech. 40, 941–946. http://dx.doi.org/10.1016/j.jbiomech.2006.02.011.

Milne, A.D., Chess, D.G., Johnson, J.A., King, G.J., 1996. Accuracy of an electromagnetic tracking device: a study of the optimal range and metal interference. J. Biomech. 29, 791–793. http://dx.doi.org/10.1016/0021-9290(96)83335-5.

Ohl, X., Hagemeister, N., Zhang, C., Billuart, F., Gagey, O., Bureau, N.J., Skalli, W., 2015. 3D scapular orientation on healthy and pathologic subjects using stereoradiographs during arm elevation. J. Shoulder Elb. Surg. http://dx.doi.org/10.1016/j.jse.2015.04.007.

Paletta Jr., G.A., Warner, J.J., Warren, R.F., Deutsch, A., Altchek, D.W., 1997. Shoulder kinematics with two-plane x-ray evaluation in patients with anterior instability or rotator cuff tearing. J. Shoulder Elb. Surg. 6, 516–527. http://dx.doi.org/10.1016/S1058-2746(97)90084-7.

Park, H.B., Yokota, A., Gill, H.S., El, R.G., McFarland, E.G., 2005. Diagnostic accuracy of clinical tests for the different degrees of subacromial impingement syndrome. J. Bone Joint Surg. Am. 87, 1446–1455. http://dx.doi.org/10.2106/jbjs.d.02335.

Parsons, I.M., Apreleva, M., Fu, F.H., Woo, S.L., 2002. The effect of rotator cuff tears on reaction forces at the glenohumeral joint. J. Orthop. Res. 20, 439–446. http://dx.doi.org/10.1016/S0736-0266(01)00137-1.

Picavet, H.S., Schouten, J.S., 2003. Musculoskeletal pain in the Netherlands: prevalences, consequences and risk groups, the DMC(3)-study. Pain 102, 167–178. http://dx.doi.org/10.1016/s0304-3959(02)00372-x.

Scibek, J.S., Mell, A.G., Downie, B.K., Carpenter, J.E., Hughes, R.E., 2008. Shoulder kinematics in patients with full-thickness rotator cuff tears after a subacromial injection. J. Shoulder Elb. Surg. 17, 172–181. http://dx.doi.org/10.1016/j.jse.2007.05.010.

Steenbrink, F., de Groot, J.H., Veeger, H.E., Meskers, C.G., van de Sande, M.A., Rozing, P.M., 2006. Pathological muscle activation patterns in patients with massive rotator cuff tears, with and without subacromial anaesthetics. Man. Ther. 11, 231–237. http://dx.doi.org/10.1016/j.math.2006.07.004.

Steenbrink, F., de Groot, J.H., Veeger, H.E., van der Helm, F.C., Rozing, P.M., 2009. Glenohumeral stability in simulated rotator cuff tears. J. Biomech. 42, 1740–1745. http://dx.doi.org/10.1016/j.jbiomech.2009.04.011.

Steenbrink, F., Meskers, C.G., Nelissen, R.G., de Groot, J.H., 2010a. The relation between increased deltoid activation and adductor muscle activation due to glenohumeral cuff tears. J. Biomech. 43, 2049–2054. http://dx.doi.org/10.1016/j.jbiomech.2010.04.012.

Steenbrink, F., Nelissen, R.G., Meskers, C.G., van de Sande, M.A., Rozing, P.M., de Groot, J.H., 2010b. Teres major muscle activation relates to clinical outcome in tendon transfer surgery. Clin. Biomech. 25, 187–193. http://dx.doi.org/10.1016/j.clinbiomech.2009.11.001.

Thompson, W.O., Debski, R.E., Boardman III, N.D., Taskiran, E., Warner, J.J., Fu, F.H., Woo, S.L., 1996. A biomechanical analysis of rotator cuff deficiency in a cadaveric model. Am. J. Sports Med. 24, 286–292. http://dx.doi.org/10.1177/036354659602400307.

Veeger, H.E., van der Helm, F.C., 2007. Shoulder function: the perfect compromise between mobility and stability. J. Biomech. 40, 2119–2129. http://dx.doi.org/10.1016/j.jbiomech.2006.10.016.

Verbeke, G., Molenberghs, G., 2009. Linear Mixed Models for Longitudinal Data, third ed. Springer Science & Business Media, New York.

van der Windt, D.A., Koes, B.W., de Jong, B.A., Bouter, L.M., 1995. Shoulder disorders in general practice: incidence, patient characteristics, and management. Ann. Rheum. Dis. 54, 959–964. http://dx.doi.org/10.1136/ard.54.12.959.

de Witte, P.B., van der Zwaal, P., van Arkel, E.R., Nelissen, R.G., de Groot, J.H., 2013. Pathologic deltoid activation in rotator cuff tear patients: normalization after cuff repair? Med. Biol. Eng. Comput. http://dx.doi.org/10.1007/s11517-013-1095-9.

Wu, G., van der Helm, F.C., Veeger, H.E., Makhsous, M., Van, R.P., Anglin, C., Nagels, J., Karduna, A.R., McQuade, K., Wang, X., Werner, F.W., Buchholz, B., 2005. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion—part II: shoulder, elbow, wrist and hand. J. Biomech. 38, 981–992. http://dx.doi.org/10.1016/j.jbiomech.2004.05.042.

Yamaguchi, K., Sher, J.S., Andersen, W.K., Garretson, R., Uribe, J.W., Hechtman, K., Neviaser, R.J., 2000. Glenohumeral motion in patients with rotator cuff tears: a comparison of asymptomatic and symptomatic shoulders. J. Shoulder Elb. Surg. 9, 6–11. http://dx.doi.org/10.1016/S1058-2746(00)90002-8.