Functional implications of structural “anomalies” in shoulder pain

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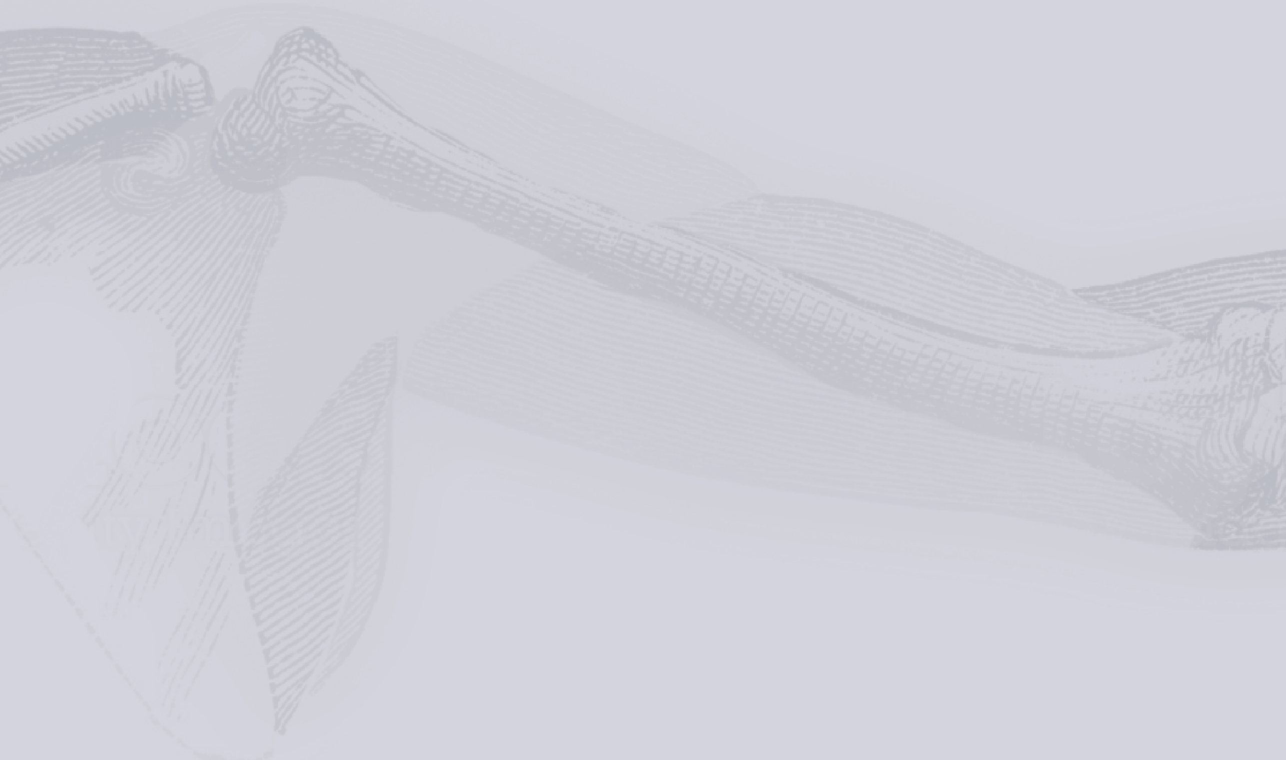

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Kinematics and muscle activation in subacromial pain syndrome patients and asymptomatic controls

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ABSTRACT

Background: Conflicting theories exist about the underlying cause of chronic subacromial pain in the middle-aged population. Understanding the kinematics and muscle activation provide insight in the pathophysiology of subacromial pain syndrome.

Methods: In a cross-sectional comparison of 40 patients with subacromial pain syndrome and 30 asymptomatic controls, we quantified independently recorded three-dimensional shoulder kinematics and electromyography-based co-contraction in 10 shoulder muscles. Glenohumeral and scapulothoracic kinematics were evaluated during abduction and forward flexion. Co-contraction was expressed as an activation ratio, specifying the relative agonistic and antagonistic muscle activity in each muscle.

Results: During abduction and forward flexion, the contribution of glenohumeral motion to elevation (e.g. at 120^0 abduction: -9°, 95% confidence interval -14°- -3°, P = 0.003) and external rotation (e.g. at 120^0 abduction: -8°, 95% confidence interval -13°--3°, P < 0.001) was lower in subacromial pain syndrome, and was compensated by more scapulothoracic motion. The pectoralis major's activation ratio was significantly lower (Z-score: -2.657, P = 0.008) and teres major's activation ratio significantly higher (Z-score: -4.088, P < 0.001) in patients with subacromial pain syndrome compared to the control group.

Conclusions: Reduced glenohumeral elevation and glenohumeral external rotation in subacromial pain syndrome coincided with less teres major antagonistic activity during elevation. These biomechanical findings may initiate intervention studies directed at stretching exercises to reduce glenohumeral stiffness in the treatment of subacromial pain syndrome, and teres major strengthening to improve humeral head depressor function.

INTRODUCTION

Subacromial Pain Syndrome (SAPS), previously known as subacromial impingent syndrome, is the most frequently diagnosis in shoulder pain and functional deficit in our society with a prevalence up to 48 per 1000 person-years.[18] SAPS predominantly affect patients between 30 and 60 years of age implying an irrefutable impact on sick leave from work and health care costs.[49] More pathophysiologic mechanisms than "*impingement*" alone are suggested, and there are currently no well-proven approaches to differentiate these mechanisms. Therefore, we considered SAPS a syndrome.[3, 12] While SAPS has a high prevalence and large economic burden, we still do not entirely understand its pathophysiology nor its manifestations.[12] More understanding of SAPS is essential to unravel its pathophysiology and develop more patient specific treatment modalities.

Many studies have focussed on the role of muscle activity and kinematics in the pathophysiology of subacromial pain due to their influence on the subacromial space width, but findings regarding scapular stabilizers (i.e. reduced/increased activity of the trapezius and serratus anterior) and shoulder kinematics (i.e. less or more scapulothoracic lateral rotation) are inconsistent.[14, 23, 27, 29, 30, 35] Different definitions of subacromial impingement syndrome may partially explain these inconsistencies.[12] For example, patients with rotator cuff (RC) tears have been included in many studies on impingement syndrome, since RC tears were considered the end-stage of impingement syndrome for years. Nowadays, SAPS is generally distinguished from a full-thickness RC tear.[12, 38] Moreover, the lack of accurate clinical tests to confirm SAPS and its uniform interpretation are likely to contribute to heterogeneity in study populations, and result in inconsistent study outcomes.[12, 44] Study outcomes in SAPS and shoulder biomechanics are probably better understood in more homogenous groups with a more comparable anatomic substrate (e.g. bursitis, tendinopathy) for subacromial pain syndrome on Magnetic Resonance Imaging (MRI).

This study aims to evaluate shoulder muscle activity as well as kinematics in a homogenous group of patients with SAPS, selected after clinical *and* radiologic examination. Results were compared to a control group with asymptomatic subjects. We hypothesized that subacromial movements in the SAPS group provoke a painful stimulus resulting in reduced glenohumeral kinematics, and more co-contraction of glenohumeral and thoracohumeral adductor muscles and scapulothoracic muscles to clear subacromial tissues. We formulated the following questions: (1) Do patients with SAPS show less glenohumeral elevation and more scapulothoracic motion (i.e. internal rotation, lateral rotation and posterior tilt) compared to asymptomatic controls? (2) Do patients with SAPS have different co-contraction patterns of scapulothoracic, glenohumeral and humerothoracic muscles compared to asymptomatic controls?

MATERIALS AND METHODS

Study design

In this cross-sectional study we evaluated shoulders of patients with SAPS and asymptomatic controls at the Laboratory for Kinematics and Neuromechanics (Leiden University Medical Center, Leiden, the Netherlands) and compared shoulder muscle activation patterns and kinematics between both study groups (Level of evidence II). The institutional medical ethical review board approved this study (protocol numbers: P09.227 and P15.046) and written informed consent was obtained from all participants.

Participants

The SAPS group consisted of patients aged between 35-60 years with unilateral subacromial shoulder pain for at least 3 months, who were recruited from April 2010 to November 2016 at the outpatient clinics of three participating hospitals (Leiden University Medical Centre, Medical Centre Haaglanden and Alrijne Hospital). The diagnosis was confirmed by an orthopaedic shoulder surgeon (JN, RN CPJV, ERAvA) by history taking and physical examination. Alternative causes for shoulder pain were excluded using radiographs and magnetic resonance imaging (MRI) arthrography. SAPS was defined as a positive Hawkins and Neer impingement test in combination with one or more of the following findings: pain during shoulder movement, pain at night or incapable to lay on the shoulder, painful arc, diffuse pain upon palpation of the greater tuberosity, scapular dyskinesis, a positive full/empty can test or a positive Yocum test. Exclusion criteria were insufficient Dutch language skills, prior shoulder surgery, shoulder fracture or dislocation, radiculopathy, frozen shoulder, electronic implants, clinical signs of (inflammatory) glenohumeral or symptomatic acromioclavicular osteoarthritis, calcific tendinitis, full-thickness RC tear, labrum or ligament pathology, pulley lesion, biceps tendinopathy, os acromiale and tumor. Some of these patients may also have participated in previous studies.[13, 21, 22, 40, 41]

The control group consisted of age- and sex-matched asymptomatic subjects without current or past shoulder complaints. The affected side of these matched counterparts in the SAPS group dictated the shoulder of interest in asymptomatic controls. The control group was recruited between January 2016 and November 2016 by contacting spouses of patients from the outpatient clinic at the Leiden University Medical Center. All asymptomatic controls had a score of <10mm on a Visual Analogue Scale (VAS, 0-100mm, 0 indicated no shoulder pain and 100 severe shoulder pain), did not visit a physician for shoulder related complaints and did not report shoulder discomfort for more than one week in their past. Exclusion criteria were impaired shoulder function during physical examination, insufficient Dutch language skills, prior shoulder surgery or injections, shoulder fracture or dislocation, radiculopathy, frozen shoulder, electronic implants, symptomatic osteoarthritis or rheumatoid arthritis and neurologic or muscle disease.

Demographics

Clinical shoulder function was evaluated in all participants using the following questionnaires: VAS for pain at rest, during arm movement and shoulder functionality during daily tasks (0-100mm, 0mm indicating absence of pain/perfect shoulder function and 100mm indicating severe shoulder pain/impaired shoulder function); Constant Score (CS).[6] Quality-of-life was calculated using the RAND-36 using Dutch normative data.[1, 47] In addition, shoulder function was quantified using humerothoracic range of motion (RoM) from our three-dimensional electromagnetic motion analysis (Flock of Birds).

Conventional anteroposterior radiographs were used to define the 1) acromiohumeral (AH) interval, 2) upward migration index (UMI), 3) scapular spine-humeral head center (SHC), 4) Critical Shoulder Angle (CSA), and the 5) Acromion Index (AI).[36, 37, 39]

Rotator cuff imaging: In the SAPS group MR arthrography was performed using a standardised protocol on 3 T MR (the following sequences were performed; coronal oblique T2 weighted Turbo Spin echo (TSE) with fat suppression (FS); after intravenous administration of diluted gadolinium chelate coronal oblique, sagittal oblique and axial T1 TSE FS, sagittal oblique T1 TSE). These images were evaluated by a musculoskeletal radiologist (ANC & MR) for the presence of a partial or full-thickness RC tear, tendinopathy, bursitis and acromioclavicular osteoarthritis and/or synovitis. All shoulders of asymptomatic controls were screened with ultrasound.to check for an RC tear without the need for an invasive intra-articular procedure. Ultrasound has a similar high sensitivity and specificity compared with MR arthrography to detect full thickness RC tears[11, 24] A musculoskeletal radiologist (ANC or MR) screened for the presence of (asymptomatic) partial or full-thickness RC tears, tendinopathy, bursitis and acromioclavicular osteoarthritis and/or synovitis using a linear 12 MHz transducer.

Three-dimensional electromagnetic motion analyses

Measurement set-up: Measurement methodology was previously described.[21, 22] This methodology has been validated in previous studies to examine bilateral shoulder motion with six degrees of freedom.[7, 32] A detailed description of our measurement set-up and data processing are given in supplement 1. In brief, shoulder kinematics were recorded using the Flock of Birds (FoB) tracking device (Ascension Technology Inc., Milton, Vermont, USA) with seven wired sensors to describe 1) segment orientations (Cardan angles) of the humerus and scapula relative to the thorax (i.e. humerotoracic and scapulothoracic, respectively) and 2) humeral orientations relative to the scapula (i.e. glenohumeral). Sensor position and bony landmarks were determined according to the International Society of Biomechanics (ISB).[50] Patients were instructed to complete abduction and forward flexion bilaterally, unguided by any aids. The bony landmarks were used to reconstruct a local Cartesian right-handed coordinate system for the thorax, scapula and humerus according to Wu et al..[50] Humerothoracic (HT) orientation was described by 1) plane of elevation; 2) elevation; and 3) internal rotation. Glenohumeral (GH) orientation was described by: 1) GH plane of elevation; 2) GH elevation; and 3) internal GH axial rotation. Scapulothoracic (ST) orientation was described by: 1) internal rotation (i.e. protraction); 2) lateral rotation (i.e. upward rotation); and 3) posterior tilt. HT elevation, ST lateral rotation and GH elevation were described as positive motions, which is in contrast to Wu et al..[50] Custom made MATLAB 2013b (The MathWorks Inc., Natick, Massachusetts, USA) software was used for data processing.

Outcome measures: The primary outcome was three-dimensional GH and ST angles from the kinematic analyses. These were calculated for abduction and forward flexion up to 120° of HT elevation, because of skin motion artifacts of the scapular sensors at higher elevation angles.[20] The HT plane of elevation were checked to secure the correct description of abduction (HT plane of elevation <30°) and forward flexion motions (HT plane of elevation >45°),. Out of plane observations were discarded. Data of two repeated movements were averaged at ten intervals with 10° increments of HT elevation.

Range of Motion (RoM) was quantitatively expressed as maximal HT movement on the side of interest. HT movement does not require data from the acromial sensor and can be described over 120° HT elevation.

Electromyography and muscle activation

Measurement set-up and data processing: To compare muscle activity around the glenohumeral (GH) joint between SAPS and asymptomatic controls, we applied the proven measurement set-up with excellent reliability and accuracy.[8, 31, 33, 46] A detailed description of the EMG measurement set-up and data processing is given in supplement 2. In brief, patients were seated with the arm of interest in a splint with the upper arm in one position (30° from frontal plane; 60° elevation; and 45° internal rotation). Except for the forces of interest in the plane perpendicular to the humerus, all gravitational forces and GH moments were neutralized by contra-weights. Bi-polar surface electromyography (EMG) was used to record muscle activation from 10 muscles: 1) m. trapezius pars descendens; 2) m. trapezius pars ascendens; 3) m. deltoideus, pars clavicularis; 4) m. deltoideus, pars acromialis; 5) m. deltoideus, pars spinalis; 6) m. infraspinatus; 7) m. serratus anterior; 8) m. latissimus dorsi; 9) m. pectoralis major, pars clavicularis; and 10) m. teres major. Subjects were instructed to complete a rest task and 24 random isometrical force tasks by moving a visually controlled cursor to a goal position, and keeping it for 2 seconds. The goal positions represented humeral forces of equal magnitude with 15° increments in a range from 0-360°. Force and EMG signals were simultaneously recorded and sampled at a rate of 2000Hz. The 2 second EMG signal during were rectified and averaged (aEMG). The rectified EMG signal at rest was subtracted from the aEMG signals during the active tasks resulting in the rEMG.

Outcome measures: Muscle activity was expressed using two outcome measures: 1) activation ratio (AR), and 2) principle action. Tasks were categorised as agonist 'in-phase' or antagonist 'out-of-phase' activity for each muscle according to definitions obtained from previous work.[2, 46] Subsequently, the activation ratio (AR) was calculated by taking the rEMG over the muscle specific in-phase ($rEMG^{IP}$) and out-phase tasks ($rEMG^{OP}$) applying the following formula.

$$AR = \frac{rEMG^{IP} - rEMG^{OP}}{rEMG^{IP} + rEMG^{OP}} \quad where \quad [-1 \leq AR \leq 1]$$

The AR can range from -1 to 1, where an AR of 1 indicates maximal agonistic activity without any activity during the opposite antagonistic task. Negative ARs indicate more muscle activity during antagonistic tasks than agonistic tasks. Since the AR relates isometrically recorded and relative magnitude of EMG of individual muscles as a function of direction direction, it is less influenced by differences skin resistance, maximum voluntary contraction (MVC) or electrode position when comparing groups.

The principal action (PA) ranges from 0° to 360° (clockwise rotation, 0° and 360° at 12 o'clock) indicating the angle of the external force vector (i.e. task) where the muscle is most active. The PA was obtained by applying a function that was fitted onto the rEMG signals from 24 tasks using a least square method [8]. Using this method two amplitude parameters (A_0: Baseline muscle activation and A_{pa}: maximal muscle activation) and three directional parameters (*PA*: angle of maximum or principle activation, I_1: clockwise onset of muscle activation, I_2: clockwise offset of muscle activation)[8]. All data were processed using custom made software MATLAB 2013b (The MathWorks Inc., Natick, Massachusetts, USA).

Statistical analysis

Sample size: Prior to our study, we calculated the required sample size for our primary outcome ST upward rotation and GH glenohumeral elevation aimed to detect a difference of 10° and accounted for a liberal standard deviation of 10°.[27, 29, 30] Based on a standardized difference of 1.0 (10°/10°), a power of 80% and a two-sided a of 0.05, the Altman's Nomogram indicated a minimally required number of 30 subjects in each group. Thus, data from available 40 SAPS patients were used, 30 asymptomatic subjects were recruited for the control group.

Data analysis: Categorical data were described with numbers and percentage, non-parametric data with a median and 25th to 75th percentile and parametric data with mean and standard deviation. Demographics including questionnaires, radiographic and EMG outcomes between groups were compared using Pearson Chi^2 test, Wilcoxon signed rank test or Student's t-test when appropriate. Mean differences were expressed as mean and 95% confidence intervals (95%CI). The analysis of shoulder kinematics involves correlated errors while raising the arm. We therefore compared the GH and ST rotation between study groups with a linear mixed model analysis and modelled covariance with an 'unstructured' covariance structure. The dependent variable was a single shoulder rotation from our kinematic data. We included humerothoracic elevation interval and the interaction between group (i.e. SAPS versus control) with humerothoracic elevation interval as fixed effects. The repeated factor was the humerothoracic elevation interval. Because the arm movement tasks were unguided, differences in plane of elevation and axial humeral rotation may have affected shoulder kinematics. Therefore, we included these potential deviating rotations as a covariate.[28] Correspondingly, we adjusted for age (years), sex (male/female) and whether the dominant side was studied. We used IBM SPSS statistics for Windows (version 20.0, IBM Corp, 2011, Armonk, New York, USA). A 2-sided P-value <0.05 was considered statistically significant.

RESULTS

Demographics and clinical characteristics

Forty SAPS patients and thirty asymptomatic controls participated in this study. The number of eligible patients and excluded SAPS patients are presented in Figure 1. The mean age was 50 versus 51 years and the number of female participants was 58% versus 57% in the SAPS and control group, respectively. There were no significant differences with respect to demographics between both groups (Table 1). The median VAS-pain score was 2mm (out of 100mm) in the control group, consistent with no reported pain. The SAPS group scored significantly lower on the CS, quantitative range of motion (i.e. Flock of Birds) and several domains of quality-of-life (Table 1).

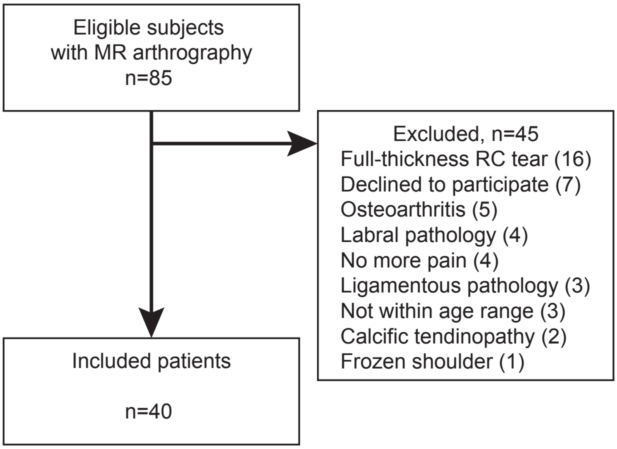

Figure 1. Flow-chart of eligible SAPS participants and reasons for exclusion.

Table 1. Demographics and clinical characteristics

	SAPS (n=40)		Controls (n=30)		Between-group Difference	
					Mean (95% CI) or Chi-square score	*P value*
Age (yrs.) †	50	(6.4)	51	(5.7)	0 (-2.5 – 3.4)	0.740
Female (n, %) ‡	23	(58%)	17	(57%)	0.005	0.944
Affected/studied arm, left (n, %) ‡	16	(40%)	12	(40%)	0.000	1.000
Dominant arm, left (n, %) ‡	5	(13%)	5	(17%)	0.243	0.622
Dominant arm studied (n, %) ‡	25	(63%)	17	(57%)	0.243	0.622
Questionnaires						
VAS pain, rest (mm)**	12	(2 – 28)	2	(1 – 3)	-4.096	<0.001*
VAS pain, movement (mm)**	40	(18 – 60)	2	(1 – 3)	-6.690	<0.001*
VAS shoulder functionality (mm)**	36	(21 – 56)	2	(1 – 3)	-6.520	<0.001*
Constant Score (points) †	70	(12.7)	94	(4.1)	-23 (-28.1 – -19.5)	<0.001*
RAND-36 (points) †						
- Physical Functioning	76	(14.4)	94	(9.8)	-18 (-24.1 – -11.9)	<0.001*
- Role-Physical	59	(41.0)	95	(19.0)	-36 (-51.0 – -21.5)	<0.001*
- Bodily Pain	57	(17.5)	94	(11.8)	-36 (-43.8 – -29.0)	<0.001*
- General Health	63	(21.7)	76	(16.0)	-13 (-21.9 – -3.9)	0.006*
- Vitality	63	(15.8)	76	(17.6)	-12 (-20.3 – -4.3)	0.003*
- Social Functioning	80	(19.0)	89	(20.3)	-8 (-17.9 – 1.0)	0.079
- Role-Emotional	85	(32.9)	92	(24.3)	-7 (-21.4 – 7.0)	0.314
- Mental Health	75	(15.7)	83	(14.4)	-8 (-15.2 – -0.5)	0.036*
Health change	48	(24.3)	55	(15.3)	-7 (-16.3 – 2.6)	0.152
Quantitative Range of Motion (i.e. Humerothoracic)						
Abduction (°)†	136	(23.6)	157	(8.3)	-21 (-29.9 – -12.7)	<0.001*
Forward flexion (°)†	138	(17.2)	154	(7.8)	-16 (-22.4 – -10.1)	<0.001*
Extension (°)†	54	(12.0)	69	(8.8)	-14 (-19.5 – -9.0)	<0.001*
External rotation (°)†	81	(14.3)	84	(16.8)	4 (-3.8 – -11.1)	0.332

Demographics of both groups including clinical shoulder function and quantitative range of motion measured with Flock of Birds in the SAPS and control group. Abbreviations: SAPS, Subacromial Pain Syndrome; CI, Confidence Interval; yrs, years; n, number; mm, millimeter.

† Data are presented as mean with standard deviation and compared with the Student's t-test.

‡ Data are presented as number and percentage within group and compared with the Pearson Chi-square.

** Data are presented as median (25th and 75th percentile) and was compared with the Wilcoxon signed rank test.

* Statistically significant (P < 0.05).

Radiographs did not demonstrate structural differences regarding the anatomic GH relationship (Table 2). We found one asymptomatic partial-thickness and one asymptomatic full-thickness rotator cuff tear in the control group. Therefore, we conducted analyses with (because asymptomatic) and without (because a structural defect influences biomechanics) these two asymptomatic controls, but findings of the analysis were comparable and did not lead to different conclusions. Consequently, we present the results including all asymptomatic controls.

Table 2. Radiologic findings

		SAPS (n=40)		**Controls** (n=30)		**Between-group difference**	
						95% CI or Chi-square value	*P value*
Radiography							
AH interval (mm) [†]		12	(2.5)	11	(2.3)	0 (-0.8 – 1.5)	0.519
UMI (ratio) [†]		1.4	(0.09)	1.4	(0.07)	0.0 (-0.03 – 0.05)	0.608
SHC (mm) [†]		-1.9	(4.75)	-0.4	(4.66)	-1.5 (-3.72 – 0.82)	0.207
Critical Shoulder Angle (°) [†]		33	(2.9)	34	(3.3)	-1 (-2.4 – 0.6)	0.223
Acromion Index (GA/GH) [†]		0.8	(0.85)	0.7	(0.07)	0.1 (-0.17 – 0.45)	0.304
RC imaging[‡]							
SSp:	Full-thickness tear	0	(0%)	1	(3%)		
	Partial-thickness						
	- Articular	8	(20%)	1	(3%)		
	- Bursal	2	(5%)	0	(0%)		
	Tendinopathy	30	(75%)	9	(30%)		
ISp:	Full-thickness tear	0	(0%)	0	(0%)		
	Partial-thickness						
	- Articular	8	(20%)	0	(0%)		
	- Bursal	0	(0%)	0	(0%)		
	Tendinopathy	7	(18%)	4	(13%)		
SSc:	Partial tear	0	(0%)	0	(0%)		
Bursitis		22	(55%)	0	(0%)		
Acromioclavicular osteophytes		17	(43%)	3	(10%)		
Acromioclavicular synovitis		14	(35%)	2	(7%)		

Radiologic findings in the SAPS and control group. Abbreviations: SAPS, Subacromial Pain Syndrome; CI, Confidence Interval; yrs, years; n, number; mm, millimeter; GA, distance from the glenoid to the acromion; GH, distance from the glenoid to the lateral border of the humeral head.

[†] Data are presented as mean with standard deviation and compared with the Student's t-test.

[‡] The rotator cuff has been evaluated with MR arthrography in the SAPS group and with ultrasonography in the control group.

Do patients with SAPS show less glenohumeral and more scapulothoracic motion compared to asymptomatic controls?

The GH plane of elevation did not significantly differ between the SAPS and the control group at low elevation angles but was (i.e. 5-7°) higher in the SAPS group at 100° to 120° HT abduction. GH elevation was 3-4° lower in SAPS at initial HT elevation angles. The difference increased to 8-9° at 120° abduction and forward flexion (Figure 2, Table-S 3). There was more GH internal rotation was 8° to 11° higher during abduction in the SAPS group. GH internal rotation did not differ during forward flexion.

Because HT elevation was the task parameter, the reduction in GH elevation coincided with an increased ST lateral rotation in the SAPS group during abduction and forward flexion (Figure 3, Table-S 4). ST posterior tilt was also higher in SAPS compared to their asymptomatic counterparts during both abduction and forward flexion.

As an alternative to the absolute angles presented in Table-S 3 and in Table-S 4, we presented GH and ST motion from the initial position at 20°-30° humerothoracic elevation to 120° by incorporating the group (SAPS vs. controls) as fixed effect into our statistical analysis in Table-S 5 and Table-S 6, respectively.

Do patients with SAPS have different co-contraction of scapulothoracic muscles, glenohumeral and humerothoracic muscles compared to asymptomatic controls?

AR's were obtained for ten muscles (Figure 4, Table-S 7). The AR's of the upper and lower trapezius muscle and serratus anterior (i.e. scapulothoracic muscles) were not significantly different between the SAPS and control group. The AR of the pectoralis major was significantly lower (0.83 vs. 0.90, Z-score: -2.657, P = 0.008) in the SAPS group, which resulted from relatively less agonistic (i.e. in-phase) activity of the pectoralis major in the SAPS group (Figure-S8). The AR of the teres major was significantly higher (0.46 vs. -0.02, Z-score: -4.088, p<0.001) in the SAPS group, indicating relatively low antagonistic (i.e. out-of-phase) activity in SAPS (Figure-S8).

The PA of the muscles are described in Table 3. The PA of the upper trapezius in SAPS was more upwardly rotated (73° vs. 114°, Z-score -4.283, P < 0.001). The PA of the serratus anterior muscle in SAPS was in a significantly more upwardly rotated direction (19° vs. 31°, Z-score -2.089, P = 0.037), despite missing data due to a low signal to noise ratio. No difference in PA was found for the pectoralis major. The PA of the teres major in SAPS was significantly more active during adduction tasks (213° vs. 26°, Z-score -2.255, P = 0.024). An PA of 26° in the control group indicates a dominant activation of the teres major during abduction tasks (i.e. antagonistic activity), which coincides with a negative AR (Figure 4).

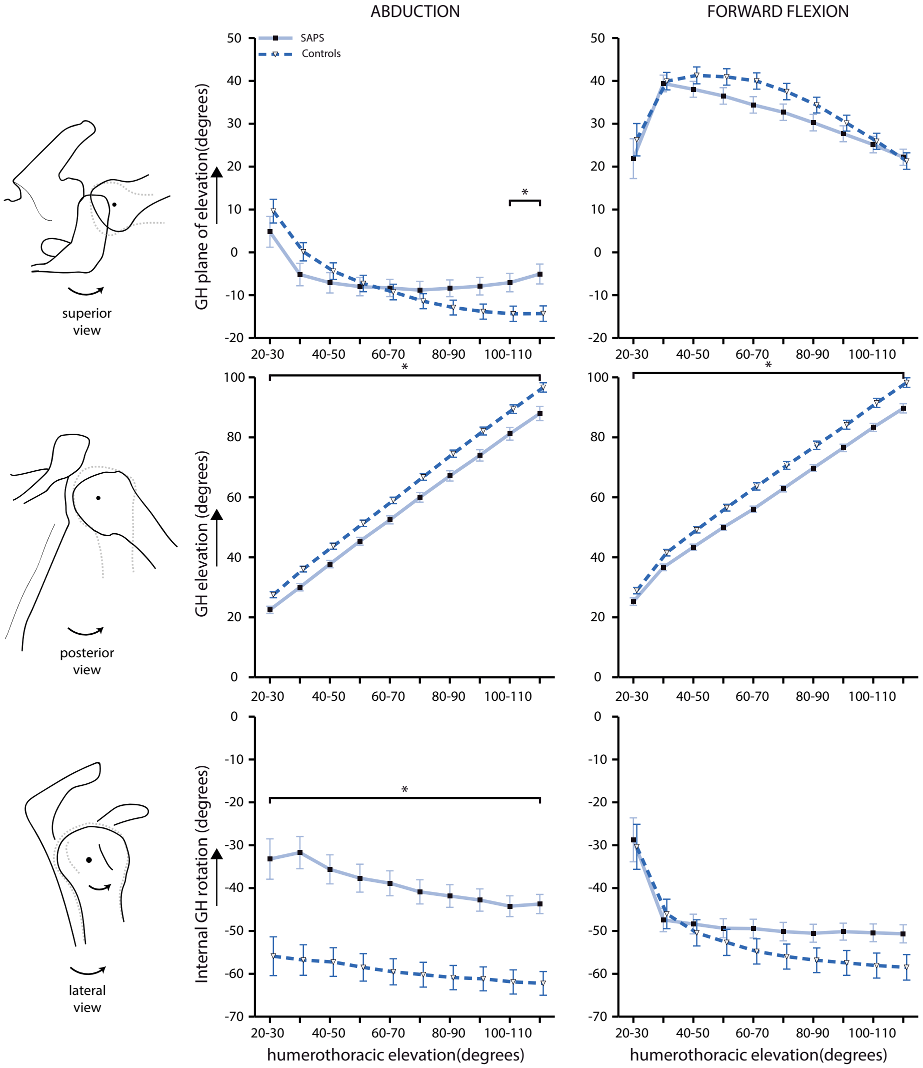

Figure 2. Graphic presentation of raw glenohumeral motion data. Glenohumeral motion (± standard error) is described from 20°-30° of humerothoracic elevation in patients with subacromial pain syndrome (SAPS, straight line) and in an asymptomatic control group (dashed line). Schematic rotations are for the right shoulder.

[*] Statistically significant difference between the SAPS and control group at $P < 0.05$.

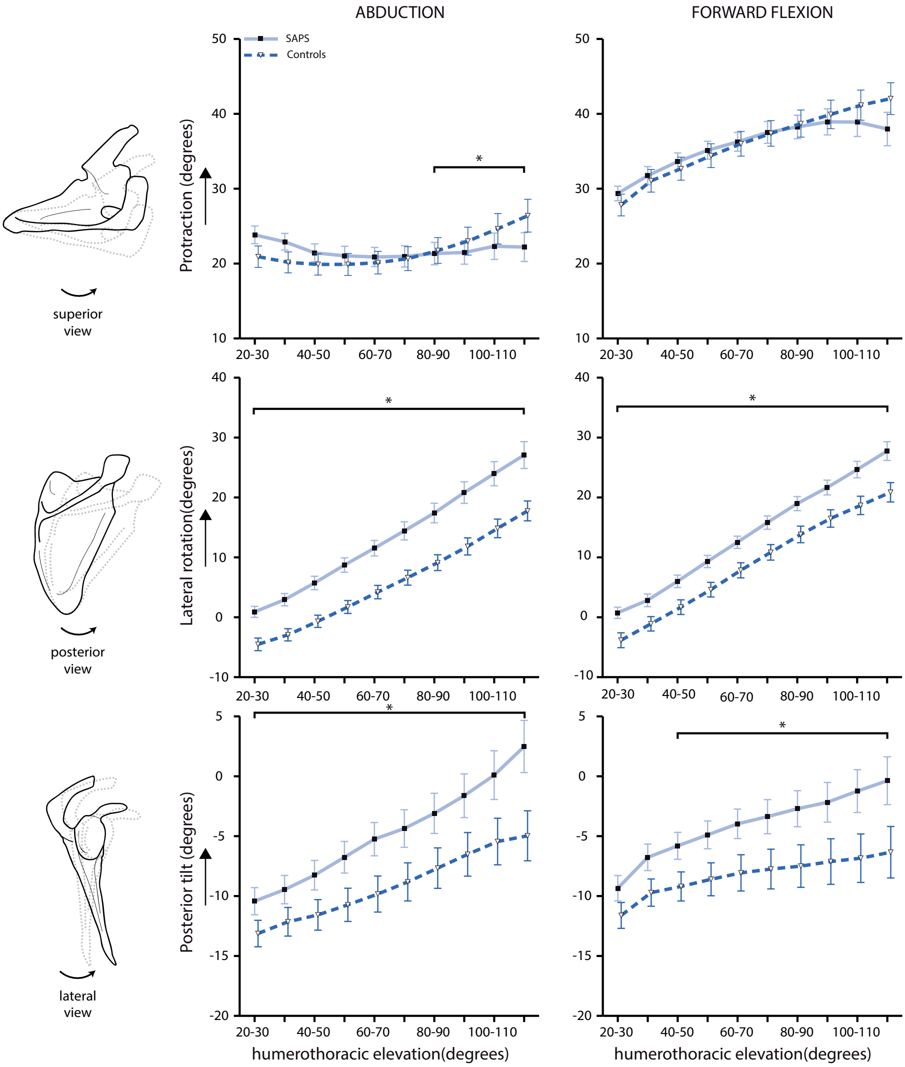

Figure 3. Graphic presentation of raw scapulothoracic motion data. Scapulothoracic motion (± standard error) is described from 20°-30° to 110°-120° of humerothoracic elevation in patients with subacromial pain syndrome (SAPS, straight line) and in an asymptomatic control group (dashed line). Schematic rotations are for the right shoulder.

[*] Statistically significant difference between the SAPS and control group at $P < 0.05$.

Table 3. Principle action

	SAPS (n=40)			**Controls** (n=30)			**Between-group difference**†	
	n	Median (°)	IQR (25 – 75th)	n	Median (°)	IQR (25 – 75th)	*Z-score*	*P value*
m. trapezius, pars descendens								
	37	73	(51.0–104.9)	*25*	114	(92.5–132.4)	-4.283	<0.001*
m. trapezius, pars ascendens								
	36	113	(95.8–139.0)	*28*	120	(91.7–132.2)	-0.528	0.103
m. deltoideus, pars clavicularis								
	39	41	(30.3–57.8)	*28*	40	(28.2–61.3)	-0.216	0.829
m. deltoideus, pars acromialis								
	39	103	(77.9–112.0)	*29*	100	(81.5–113.1)	-0.205	0.838
m. deltoideus, pars spinalis								
	39	136	(121.2–149.3)	29	128	(122.3–144.2)	-0.651	0.515
m. infraspinatus								
	23	118	(117.3–154.3)	*18*	83	(28.7–138.2)	-0.394	0.694
m. serratus anterior								
	33	19	(7.64–33.7)	*18*	31	(18.7–46.3)	-2.089	0.037*
m. latissimus dorsi								
	33	194	(170.2–212.7)	*17*	200	(181.7–213.7)	-0.707	0.480
m. pectoralis major, pars clavicularis								
	39	-7	(-24.4–0.94)	*28*	-11	(-26.4–3.11)	-0.661	0.509
m. teres major								
	35	213	(160.6–241.1)	19	26	(-5.04–212.0)	-2.255	0.024*

Principle action (PA) measurement using electromyography of ten shoulder muscles. Abbreviations: SAPS, Subacromial Pain Syndrome; n, number; IQR, interquartile range.

† Wilcoxon signed rank test.

* Statistically significant difference (P < 0.05).

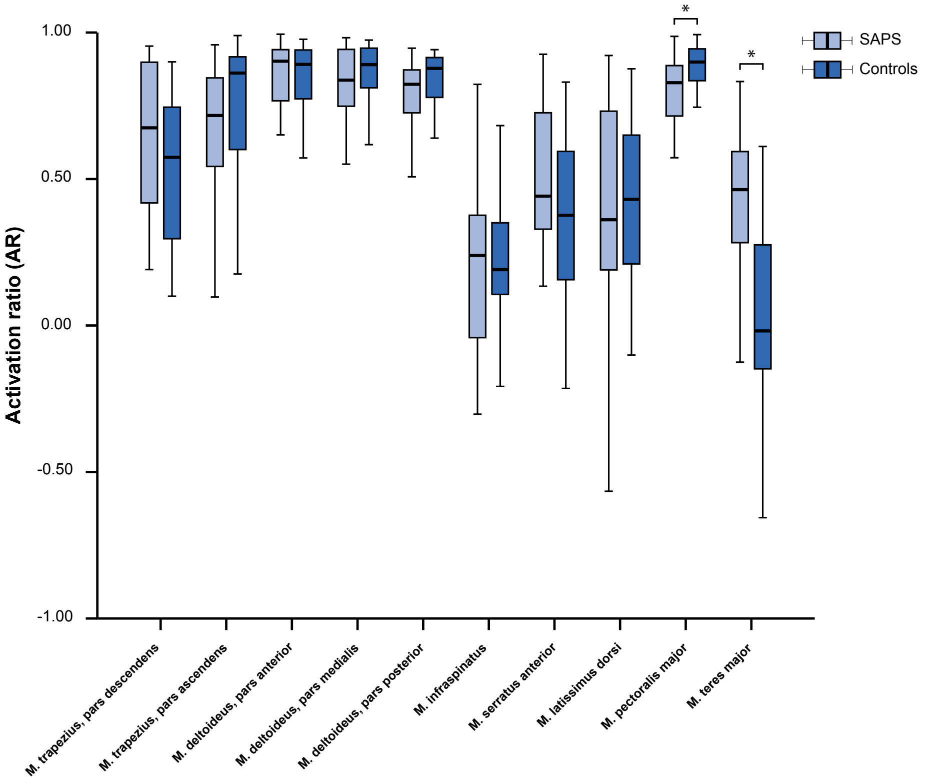

Figure 4. Boxplots (median together with 25th -75th percentile) presenting the activation ratio (AR) of ten shoulder muscles in the Subacromial Pain Syndrome group and control group.
* Statistically significant difference at $P < 0.05$.

DISCUSSION

Patients with SAPS had a lower contribution of GH elevation and GH external rotation with a higher contribution of scapulothoracic motion to overall arm movement during both abduction and forward flexion compared to asymptomatic controls. Electromyography in SAPS patients showed relatively less agonistic activity of the pectoralis major (i.e. lower AR) and less antagonistic activity of the teres major (i.e. higher AR) during isometric force tasks than controls. We did not observe a significant difference in the role of scapular stabilizer muscles (i.e. serratus anterior and trapezius muscles) during the isometric force tasks.

Many authors linked deficits in shoulder muscle activation to SAPS pathogenesis.[4, 14, 25-27, 35] The majority of studies have reported increased activity of the upper trapezius muscle and decreased activity in lower trapezius and serratus anterior.[14, 26, 27] These studies mainly focused on EMG signals obtained during force exertion in a single direction as a maximum voluntary contraction (MVC) or expressed EMG as ratio between different muscles.[4, 14, 26, 27,

[35] The principle action method from this study demonstrated that the change in activation amplitude is force direction dependent, which makes comparison with MVC tasks more speculative. MVC is an absolute parameter that is to a large extend influenced by pain.[15] Alternatively, we reduce the effect of pain, skin resistance and electrode position, by relating EMG to force direction with the use of AR. The AR is less sensitive to small changes in PA direction. The difference in PA of the upper trapezius and the serratus anterior between both groups did not become apparent in the AR. However, the AR changes of the teres major coincided with a nearly opposite PA in SAPS relative to controls. Although the teres major has an adductor orientation in both groups, it was principally active during abduction in controls, indicating more co-contraction in controls. In SAPS, the pectoralis major was relatively more active during HT abduction force task, without changing its inward directed PA.

We were unable to directly compare our results with literature, since no other study groups have reported on this relative muscle activity of a single muscle over multidirectional isometric tasks in SAPS. Muscle activity of the pectoralis major and teres major has not been extensively examined in SAPS. Reduced co-contraction of arm adductors as observed in SAPS may result in more upwardly directed translation.[17] Thus, the teres major may serve as an essential humeral head depressor that prevents increased pressure on subacromial tissues in asymptomatic shoulders. A comparable mechanism plays a role in massive rotator cuff tears, in which increased teres major moments during abduction have been found to counteract (painful) cranially directed destabilizing GH forces.[10, 45, 46] An essential function as shoulder depressor would explain the association between an increase in teres major co-activation and a favourable course of complaints in patients.[42]

For shoulder kinematics, McClure at al. found, in agreement with our findings, more ST lateral rotation and more posterior tilt in SAPS patients. Those patients were recruited from an orthopaedic clinic (mean age 45 years) following physical examination, but without rotator cuff imaging and were compared to age- and sex- matched asymptomatic controls.[30] In contrast, others reported less lateral rotation and less posterior tilt in SAPS.[23, 26, 27, 29] Static measurements or the use of bone fixed sensors may partially explains differences between the outcomes.[23, 29] Alternatively, demographic differences among the examined study groups those studies are likely to impair the comparison of outcomes. Prior studied groups included male construction workers, symptomatic subjects recruited from universities and the surrounding area, or young overhead athletes.[23, 26, 27] Those symptomatic subjects don't necessarily represent SAPS patients that were recruited from three orthopaedic outpatient clinics after ruling out alternative diagnoses by RC imaging in our study. Since clinical tests have limited accuracy to exclude alternative diagnoses, we exposed patients to X-rays and MR imaging and found an RC tear in 19% (Figure 1) of patients initially diagnosed with SAPS.[44] All above mentioned factors will contribute to heterogeneity in study populations, and thus inconsistent study outcomes.

The relation between the observed kinematics and muscle activity is speculative, since outcomes were obtained in two separate measurements. Both outcomes were separately obtained because interference of electromagnetic tracking and EMG recordings. Muscle activity controls scapular and humeral position (i.e. muscle activity influences the orientation of bones). In turn, scapular and humeral position (i.e. kinematics) impact resultant muscle strain or strain rate, and thus bone orientation impact muscle activity (EMG). We observed an association between reduced antagonistic teres major activation and reduced GH elevation. This may reflect a trade-off between GH joint stability (by increased teres major coactivation the humeral head is pulled downwards) and glenohumeral elevation in SAPS patients. We speculate that more teres major co-activation during arm elevation creates a more stable fulcrum in asymptomatic shoulders. Subacromial inflammation prompts adhesions, which may decrease external rotation.[5] Less external rotation brings the rotator cuff in closer contact with the acromion, and increases the acromial proximity to the coracoacromial arch, which may contribute to pain.[16, 34]

For orthopaedic practice, it is interesting to notice the significant effects of age on shoulder kinematics in our statistical models (data not shown). Because SAPS and RC tears mainly occur during midlife and older age, the effect of age on kinematics has to be determined.[18] For teres major co-contraction, an age-dependent association has already been demonstrated.[40] Recently, the role of surgical decompression for SAPS has been questioned after randomised placebo-controlled studies were unable to prove its treatment benefit.[3, 43] Clinical comparable outcomes were obtained after subacromial decompression and physiotherapy, resulting in recommendations against surgery.[43, 48] If changes in pectoralis/teres major activity and limitations in glenohumeral motion play a role in the development of SAPS, the findings from this study also advocate conservative, non-surgical treatment with specified physiotherapy. For that matter stretching exercises to increase glenohumeral external rotation may have been shown more effective than unspecific exercises.[19] Secondly, these findings suggest that the teres major can be strengthened, to increase co-contraction, and to depress the humeral head.

This study has some limitations. First, surface EMG electrodes may pick up additionally EMG signal of surrounding muscle groups, also known as cross-talk (e.g. infraspinatus and teres major). Despite the presence of cross-talk, the use of surface electrodes are generally accepted as an alternative to invasive intramuscular measurement and our measurement EMG set-up has been validated and showed reliable results.[4, 14, 25-27, 31, 33, 35] Second, signal over noise ratio or technical failure impaired EMG quality in some subjects for infraspinatus, serratus anterior and latissimus dorsi resulting in missing data. These missing data are considered missing at random, and we assume it did not hamper our conclusions. Third, the estimation of glenohumeral rotation center by regression, skin-sensor artefacts and variable arm elevation velocities among recordings may introduce variability into kinematic data and may impair the interpretation of data.[9, 20, 33] Despite these potential disadvantages, validity and excellent reliability has been demonstrated for electromagnetic motion analysis.[7, 32]

CONCLUSION

We found less glenohumeral elevation and external rotation during abduction and forward flexion in patients with SAPS when compared to controls. Moreover, we found a lower AR for the pectoralis major and a higher AR for the teres major in patients with SAPS compared to asymptomatic controls. These findings indicate a relative decrease in pectoralis major agonistic activity and teres major antagonistic activity in the SAPS group. Our findings explain the potential mechanism of action of stretching exercises to increase external glenohumeral rotation and teres major strengthening exercises to depress the humeral head.

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Supplement 1. Electromagnetic motion analysis measurement set-up and data processing

Shoulder kinematics were recorded using the Flock of Birds (FoB) electromagnetic tracking system (Ascension Technology Inc., Milton, Vermont, USA). Three wired sensors were attached to both arms. The first sensor was mounted with self-adhesive tape onto the cranio-lateral acromial surface. The second and third sensor were firmly attached with a hook-and-loop fastener to the distal humerus and the third to the distal forearm. A seventh sensor was attached with self-adhesive tape onto the manubrium sternii. These sensors recorded their own position and orientation at about 30Hz in an electromagnetic field which was generated by an extended range transmitter. According to the International Society of Biomechanics (ISB), twenty-four bony landmarks were manually palpated and digitized using a sensor mounted on a stylus.[32, 50]

Patients were instructed to complete four unconstraint unguided bilaterally movements, since we assumed guided movements would not sufficiently represent daily life motion: abduction, forward flexion, extension (i.e. backward flexion) and external rotation of the upper arm with the humerus at 40^0 elevation and with the elbow 90^0 flexed. All movement were repeated.

Data processing: The twenty-four bony landmarks bony landmarks were used to reconstruct a local Cartesian right-handed coordinate system for the thorax, scapula and humerus. Left segments were mirrored to the right. The axes coordinate systems of these local pointed to anterior (X_t), superior (Y_t) and lateral to the right (Z_t). For humerothoracic and GH motion an Euler sequence (Y-X-Y) was used. Humerothoracic motion was described by 1) plane of elevation (i.e. rotation around the thoracic Y-axis, 0° is elevation in the frontal plane and 90° is elevation in the parasagittal plane); 2) elevation (i.e. negative rotation around the rotated humeral X'-axis; 3) internal rotation (i.e. positive rotation around the rotated humeral Y''-axis). The following three rotations were used to express GH motion: 1) GH plane of elevation (i.e. rotation around the scapular Y-axis); 2) GH elevation (i.e. negative rotation around the humeral X'-axis); 3) internal GH rotation (i.e. positive rotation around the longitudinal humeral Y''-axis). For scapulothoracic (ST) motion a fixed Cardan sequence (Y-X-Z) was used with 1) internal rotation (i.e. positive rotation around the thoracic Y-axis); 2) lateral rotation (i.e. negative rotation around the scapular X'-axis); 3) posterior tilt is positive rotation around the scapular Z''-axis. Humerothoracic elevation, ST lateral rotation and GH elevation were described as positive motions, which is in contrast to Wu et al.[50]. Custom made software in MATLAB 2013b (The MathWorks Inc., Natick, Massachusetts, USA) was used for data processing.

Supplement 2. EMG measurement set-up, electrode position and data processing

Patients were seated with the arm of interest in one stationary position with the arm fitted in a splint and with the elbow 90 degrees flexed. The arm was positioned with the upper arm in 60° of humerothoracic elevation, 30° relative to the frontal plane and with the arm in 45° internal rotation. Bi-polar surface electromyography (EMG) with an inter-electrode distance of 10mm and bandwidth 20-450 Hz (Bagnoli-16, Delsys, Boston, MA, USA) were attached at ten locations: 1) m. trapezius pars descendens [i.e. upper trapezius]; 2) m. trapezius pars ascendens [i.e. lower trapezius]; 3) m. deltoideus pars clavicularis; 4) m. deltoideus pars acromialis; 5) m. deltoideus pars spinalis; 6) m. infraspinatus; 7) m. serratus anterior; 8) m. latissimus dorsi; 9) m. pectoralis major; and 10) m. teres major. Attachment positions at the skin were prepared by drying, rubbing (Skin Pure, Nihon Kohden, Tokyo, Japan) and cleaning with pads dragged in 70% ethanol. Surface electrodes were attached at predefined positions using self-adhesive tape.

	Electrode position
m. trapezius pars descendens	At 2/3 on a line from C7 to trigonum spinae
m. trapezius pars ascendens	At 1/2 on a line from trigonum spinae to Th 8
m. deltoideus pars clavicularis	Middle of the muscle belly
m. deltoideus pars acromialis	2 cm below the acromion and middle of muscle belly
m. deltoideus pars spinalis	Middle of the muscle belly
m. infraspinatus	At 1/2 on a line from angulus inferior to spinae scapulae
m. serratus anterior	Sixth head below the frontal axillary fold
m. latissimus dorsi	Below (+/- 5-6cm) angulus inferior of the scapula directed towards the insertion side at the humerus.
m. pectoralis major (pars clavicularis)	Middle of the muscle belly pointing to the clavicula
m. teres major	Middle of muscle belly

All gravitational forces and GH off-set moments were neutralized by contra-weights to assure measurement of isometric muscle activity. A force transducer (ATMI-300, Advanced Mechanical Technology Inc., Wavertown, MA, USA) was mounted on a low-friction rail in line with the humerus, so that subjects could only exert horizontally and vertically directed forces perpendicular to the arm. Forces parallel to the humerus and rotational forces would result in an unacceptable change in position of the arm. The task force application of the splint was attached at approximately 20cm distal from the GH joint. Subjects were instructed to apply horizontally and vertically directed forces to move a cursor on a computer screen over twenty-four successive target positions over a range from 0-360° and held this position for 2 seconds by applying an isometric force. The order of appearance of these targets were projected in a random sequence with a minimal interval of 15 seconds between subsequent targets. Because sub-maximal force leads to an optimal signal of noise ratio, sub-maximal force was determined according to individuals' maximal voluntary force that was tolerated in all directions during one practice round. EMG signals were visually checked throughout the experiment for correct signal to noise ratio.

EMG data processing: Force and EMG signal were simultaneously recorded and analogue-to-digitally converted at a maximal sample rate 2000Hz. The raw EMG signal was on-line processed with an analogue filter (20-450Hz, Delsys, Bagnoli-16, Boston, MA, USA) and sampled at a frequency of 2000Hz. Raw EMG signal during the two seconds interval of rest and force tasks were selected, rectified (recursive Butterworth low-pass filter at 10Hz) and averaged. The rest rectified EMG (rEMG) signal was subtracted from the rEMG signals during the 24 tasks. rEMG was mathematically and controlled for signal to noise ratio per task and per muscle. The quality of rEMG signal was considered insufficient if rEMG signal did not exceed 2 times the resting rEMG signal and, if insufficient, removed from our analysis. The in-phase muscle activity of each muscle was calculated by the mean rEMG^{IP} over 7 agonistic 'in-phase' tasks around the principle action (PA). The antagonistic 'out-of-phase' activity was calculated by the mean rEMG^{OP} over the 7 opposite angles.

	In-phase	**Out-phase**
	PA task (range of tasks)	task (range of tasks)
m. trapezius pars descendens	15° (330° - 60°)	195° (150° - 240°)
m. trapezius pars ascendens	75° (30° - 120°)	255° (210° - 300°)
m. deltoideus pars clavicularis	345° (300° - 30°)	165° (120° - 210°)
m. deltoideus pars acromialis	30° (345° - 75°)	210° (165° - 255°)
m. deltoideus pars spinalis	105° (60° - 150°)	285° (240° - 330°)
m. infraspinatus	60° (15° - 105°)	240° (195° - 285°)
m. serratus anterior	345° (300° - 30°)	165° (120° - 210°)
m. latissimus dorsi	195° (150° - 240°)	15° (330° - 60°)
m. pectoralis major pars clavicularis	300° (255° - 345°)	120° (75° - 165°)
m. teres major	180° (135° - 225°)	0° (315° - 45°)

All data were processed using custom made software in MATLAB (2013b release, The MathWorks Inc., Natick, Massachusetts, USA).

Supplement 3. Three-dimensional electromagnetic motion analysis: glenohumeral kinematics

Abduction		**SAPS** (n=40)		**Controls** (n=30)		**Mean difference** (°)	
		Mean (°)	95% CI	Mean (°)	95% CI	*Mean (95% CI)*	*P value*
20-30°	*Plane*[a]	10	(4.4 – 15.4)	16	(9.9 – 22.3)	-6 (-14.5 – 1.9)	0.132
	Elevation[a]	26	(23.8 – 27.6)	29	(27.1 – 31.1)	-3 (-6.1 – -0.8)	0.012*
	Internal rotation[a]	-59	(-65.1 – -53.6)	-70	(-77.1 – -63.9)	11 (2.4 – 19.8)	0.013*
30-40°	*Plane*[a]	0	(-4.0 – 3.2)	4	(0.3 – 8.4)	-5 (-10.2 – 0.66)	0.084
	Elevation[a]	32	(30.5 – 34.4)	36	(34.3 – 38.7)	-4 (-7.0 – -1.2)	0.007*
	Internal rotation[a]	-51	(-54.7 – -47.0)	-61	(-65.8 – -57.1)	11 (4.7 – 16.3)	0.001*
40-50°	*Plane*[a]	-4	(-7.4 – -1.3)	-1	(-4.9 – 2.1)	-3 (-7.7 – 1.7)	0.211
	Elevation[a]	39	(37.2 – 41.3)	44	(41.3 – 45.9)	-4 (-7.4 – -1.2)	0.007*
	Internal rotation[a]	-47	(-50.5 – -44.0)	-57	(-60.8 – -53.3)	10 (4.8 – 14.8)	<0.001*
50-60°	*Plane*[a]	-7	(-10.2 – -4.5)	-5	(-8.7 – -2.1)	-2 (-6.3 – 2.4)	0.376
	Elevation[a]	46	(44.1 – 48.5)	51	(48.2 – 53.2)	-4 (-7.8 – -1.0)	0.011*
	Internal rotation[a]	-44	(-47.3 – -41.2)	-54	(-57.7 – -50.7)	10 (5.3 – 14.6)	<0.001*
60-70°	*Plane*[a]	-9	(-12.0 – -6.5)	-8	(-11.6 – -5.3)	-1 (-5.0 – 3.4)	0.704
	Elevation[a]	53	(50.6 – 55.3)	58	(55.2 – 60.7)	-5 (-8.6 – -1.4)	0.007*
	Internal rotation[a]	-42	(-45.1 – -39.4)	-52	(-55.3 – -48.7)	10 (5.4 – 14.1)	<0.001*
70-80°	*Plane*[a]	-10	(-13.1 – -7.8)	-11	(-14.2 – -8.1)	1 (-3.4 – 4.8)	0.726
	Elevation[a]	60	(57.3 – 62.4)	65	(62.5 – 68.5)	-6 (-9.6 – -1.7)	0.006*
	Internal rotation[a]	-41	(-43.3 – -38.0)	-50	(-53.3 – -47.0)	10 (5.4 – 13.6)	<0.001*
80-90°	*Plane*[a]	-11	(-14.0 – -8.5)	-14	(-16.8 – -10.4)	2 (-1.9 – 6.5)	0.269
	Elevation[a]	67	(63.9 – 69.5)	73	(69.7 – 76.2)	-6 (-10.6 – -1.9)	0.005*
	Internal rotation[a]	-39	(-42.0 – -36.8)	-48	(-51.5 –-45.3)	9 (5.0 – 13.0)	<0.001*
90-100°	*Plane*[a]	-12	(-14.4 – -8.8)	-16	(-18.8 – -12.2)	4 (-0.4 – 8.2)	0.077
	Elevation[a]	73	(70.0 – 76.3)	80	(76.6 – 83.9)	-7 (-11.9 – -2.3)	0.005*
	Internal rotation[a]	-38	(-40.9 – -35.5)	-47	(-49.9 – -43.6)	9 (4.4 – 12.7)	<0.001*
100-110°	*Plane*[a]	-12	(-15.0 – -8.9)	-17	(-20.9 – -13.7)	5 (0.7 – 10.1)	0.025*
	Elevation[a]	80	(76.3 – 83.1)	87	(83.3 – 91.2)	-8 (-12.7 – -2.3)	0.005*
	Internal rotation[a]	-37	(-39.7 – -34.0)	-45	(-48.4 – -41.8)	8 (3.9 – 12.6)	<0.001*
110-120°	*Plane*[a]	-12	(-15.2 – -8.7)	-19	(-22.3 – -14.9)	7 (1.7 – 11.6)	0.009*
	Elevation[a]	86	(82.1 – 89.4)	94	(90.1 – 98.5)	-9 (-14.0 – -3.0)	0.003*
	Internal rotation[a]	-36	(-38.9 – -32.8)	-44	(-47.4 – -40.3)	8 (3.3 – 12.6)	<0.001*

Supplement 3. *Glenohumeral kinematics (continued)*

Forward Flexion		**SAPS** (n=40)		**Controls** (n=30)		**Mean difference (°)**	
		Mean (°)	95% CI	Mean (°)	95% CI	*Mean (95% CI)*	*P value*
20-30°	*Plane* [a]	44	(39.4 – 49.0)	50	(44.9 – 56.0)	-6 (-13.3 – 1.0)	0.089
	Elevation [a]	30	(28.5 – 32.3)	34	(32.1 – 36.5)	-4 (-6.6 – -1.1)	0.007*
	Internal rotation [a]	-54	(-59.9 – -48.3)	-60	(-66.4 – -53.0)	6 (-3.1 – 14.3)	0.202
30-40°	*Plane* [a]	40	(36.9 – 42.4)	41	(37.4 – 43.7)	-1 (-5.1 – 3.3)	0.662
	Elevation [a]	37	(35.3 – 39.1)	42	(39.4 – 43.7)	-4 (-7.2 – -1.5)	0.004*
	Internal rotation [a]	-49	(-52.2 – -45.7)	-48	(-52.2 – -44.7)	0 (-5.4 – 4.5)	0.846
40-50°	*Plane* [a]	37	(34.5 – 39.6)	38	(35.5 – 41.4)	-1 (-5.3 – 2.5)	0.487
	Elevation [a]	43	(41.6 – 45.3)	48	(46.3 – 50.5)	-5 (-7.8 – -2.1)	0.001*
	Internal rotation [a]	-48	(-50.7 – -44.8)	-48	(-51.2 – -44.4)	0 (-4.4 – 4.5)	0.982
50-60°	*Plane* [a]	35	(32.7 – 37.5)	36	(33.5 – 39.0)	-1 (-4.8 – 2.5)	0.542
	Elevation [a]	50	(48.0 – 51.8)	55	(53.2 – 57.5)	-5 (-8.4 – -2.6)	<0.001*
	Internal rotation [a]	-48	(-50.5 – -45.1)	-48	(-51.2 – -45.0)	0 (-3.8 – 4.4)	0.885
60-70°	*Plane* [a]	33	(30.3 – 35.1)	34	(31.2 – 36.8)	-1 (-5.0 – 2.4)	0.495
	Elevation [a]	56	(53.9 – 57.9)	62	(59.9 – 64.4)	-6 (-9.3 – -3.2)	<0.001*
	Internal rotation [a]	-48	(-50.2 – -45.0)	-49	(-51.9 – -45.8)	1 (-2.8 – 5.2)	0.537
70-80°	*Plane* [a]	31	(28.1 – 33.1)	31	(28.4 – 34.2)	-1 (-4.6 – 3.1)	0.702
	Elevation [a]	62	(60.3 – 64.6)	69	(66.6 – 71.6)	-7 (-9.9 – -3.3)	<0.001*
	Internal rotation [a]	-48	(-50.6 – -45.4)	-50	(-52.7 – -46.6)	2 (-2.3 – 5.7)	0.406
80-90°	*Plane* [a]	28	(25.5 – 30.8)	28	(25.3 – 31.3)	0 (-4.1 – 3.8)	0.940
	Elevation [a]	69	(67.0 – 71.6)	76	(73.2 – 78.5)	-7 (-10.0 – -3.1)	<0.001*
	Internal rotation [a]	-48	(-50.8 – -45.5)	-50	(-53.5 – -47.4)	2 (-1.8 – 6.4)	0.262
90-100°	*Plane* [a]	26	(22.9 – 28.6)	25	(21.6 – 28.1)	1 (-3.4 – 5.2)	0.680
	Elevation [a]	76	(73.6 – 78.5)	83	(80.0 – 85.7)	-7 (-10.6 – -3.1)	0.001*
	Internal rotation [a]	-48	(-50.8 – -45.4)	-51	(-54.2 – -47.9)	3 (-1.2 – 7.1)	0.160
100-110°	*Plane* [a]	24	(20.5 – 26.7)	21	(17.7 – 24.7)	2 (-2.3 – 7.1)	0.303
	Elevation [a]	83	(80.3 – 85.6)	90	(87.2 – 93.3)	-7 (-11.3 – -3.3)	0.001*
	Internal rotation [a]	-48	(-51.2 – -45.3)	-52	(-55.0 – -48.3)	3 (-1.1 – 7.8)	0.137
110-120°	*Plane* [a]	22	(18.8 – 25.6)	18	(13.9 – 21.6)	4 (-0.68 – 9.6)	0.088
	Elevation [a]	90	(86.7 – 92.6)	97	(93.9 – 100.7)	-8 (-12.1 – -3.2)	0.001*
	Internal rotation [a]	-49	(-51.9 – -45.4)	-52	(-51.9 – -45.4)	3 (-1.5 – 8.3)	0.168

Analyses of glenohumeral motion during abduction and forward flexion using an Euler sequence (Y-X-Y): 1) GH plane of elevation around the scapular Y-axis; 2) GH elevation is a negative rotation around the rotated humeral X'-axis; and 3) internal GH rotation is a positive rotation around the longitudinal humeral Y"-axis. Abbreviations: SAPS, Subacromial Pain Syndrome; CI, Confidence Interval.

[a] Mixed model analysis with fixed effects: humerothoracic elevation angle, group (i.e. SAPS versus control) × humerothoracic elevation angle, plane of elevation, humeral axial rotation and with adjustments for age, sex (male or female) and hand dominancy (yes or no).

[*] Statistically significant difference at $P < 0.05$.

Supplement 4. Three-dimensional electromagnetic motion analysis: scapulothoracic kinematics

Abduction		**SAPS** (n=40)		**Controls** (n=30)		**Mean difference (°)**	
		Mean (°)	95% CI	Mean (°)	95% CI	*Mean (95% CI)*	*P value*
20-30°	*Internal rot.* [a]	19	(17.0 – 21.5)	20	(17.3 – 22.2)	0 (-3.8 – 2.8)	0.770
	Lateral rot. [a]	1	(-1.0 – 2.8)	-4	(-6.2 – -2.1)	5 (2.3 – 7.8)	0.001*
	Posterior tilt [a]	-8	(-10.5 – -6.5)	-12	(-14.3 – -9.9)	4 (0.7 – 6,5)	0.016*
30-40°	*Internal rot.* [a]	20	(17.7 – 21.9)	21	(18.1 – 23.0)	-1 (-4.0 – 2.4)	0.623
	Lateral rot. [a]	3	(1.0 – 4.8)	-3	(-4.7 – -0.5)	5 (2.6 – 8.4)	<0.001*
	Posterior tilt [a]	-8	(-10.0 – -5.9)	-12	(-14.2 – -9.5)	4 (0.8 – 7.0)	0.013*
40-50°	*Internal rot.* [a]	19	(17.2 – 21.6)	21	(18.5 – 23.6)	-2 (-5.0 – 1.7)	0.333
	Lateral rot. [a]	6	(3.6 – 7.6)	0	(-2.7 – 1.9)	6 (2.9 – 9.0)	<0.001*
	Posterior tilt [a]	-7	(-9.4 – -5.1)	-12	(-14.1 – -9.2)	4 (1.1 – 7.6)	0.010*
50-60°	*Internal rot.* [a]	19	(17.2 – 21.8)	22	(19.0 – 24.3)	-2 (-5.7 – 1.4)	0.227
	Lateral rot. [a]	9	(6.4 – 10.7)	2	(-0.5 – 4.5)	7 (3.3 – 9.8)	<0.001*
	Posterior tilt [a]	-6	(-8.4 – -3.8)	-11	(-13.8 – -8.4)	5 (1.4 – 8.5)	0.007*
60-70°	*Internal rot.* [a]	20	(17.3 – 22.1)	22	(19.5 – 25.1)	-3 (-6.3 – 1.1)	0.163
	Lateral rot. [a]	11	(9.0 – 13.7)	4	(1.8 – 7.1)	7 (3.3 – 10.5)	<0.00^{1*}
	Posterior tilt [a]	-5	(-7.5 – -2.5)	-10	(-13.3 – -7.5)	5 (1.6 – 9.3)	0.00^{6*}
70-80°	*Internal rot.* [a]	20	(17.4 – 22.4)	23	(20.3 – 26.1)	-3 (-7.2 – 0.5)	0.086
	Lateral rot. [a]	14	(11.8 – 16.9)	7	(3.9 – 9.8)	7 (3.6 – 11.4)	<0.001*
	Posterior tilt [a]	-4	(-6.4 – -1.0)	-10	(-12.7 – -6.5)	6 (1.8 – 10.1)	0.006*
80-90°	*Internal rot.* [a]	20	(17.6 – 22.9)	25	(21.5 – 27.7)	-4 (-8.4 – -0.2)	0.041*
	Lateral rot. [a]	17	(14.4 – 20.0)	9	(6.1 – 12.5)	8 (3.7 – 12.2)	<0.001*
	Posterior tilt [a]	-2	(-5.3 – 0.5)	-9	(-12.0 – -5.2)	6 (1.7 – 10.6)	0.007*
90-100°	*Internal rot.* [a]	21	(17.7 – 23.4)	26	(22.6 – 29.2)	-5 (-9.7 – -1.0)	0.017*
	Lateral rot. [a]	21	(17.7 – 23.7)	12	(8.5 – 15.5)	9 (4.1 – 13.4)	<0.001*
	Posterior tilt [a]	-1	(-4.1 – 2.2)	-8	(-11.3 – -3.9)	7 (1.8 – 11.5)	0.008*
100-110°	*Internal rot.* [a]	21	(18.0 – 24.4)	28	(24.0 – 31.4)	-6 (-11.4 – -1.6)	0.010*
	Lateral rot. [a]	24	(20.8 – 27.3)	15	(11.2 – 18.7)	9 (4.1 – 14.1)	0.001*
	Posterior tilt [a]	1	(-2.9 – 3.9)	-7	(-10.6 – -2.8)	7 (2.0 – 12.4)	0.007*
110-120°	*Internal rot.* [a]	22	(18.5 – 25.4)	29	(25.4 – 33.4)	-7 (-12.7 – -2.1)	0.007*
	Lateral rot. [a]	27	(23.7 – 30.6)	18	(13.8 – 21.8)	9 (4.1 – 14.6)	0.001*
	Posterior tilt [a]	2	(-1.9 – 5.4)	-6	(-10.5 – -2.1)	8 (2.5 – 13.6)	0.005*

Supplement 4. Scapulothoracic kinematics (continued)

Forward Flexion

		SAPS (n=40)		**Controls** (n=30)		**Mean difference** (°)	
		Mean (°)	95% CI	Mean (°)	95% CI	(95% CI)	P-value
20-30°	*Internal rot.* [a]	32	(29.8 – 34.2)	30	(27.8 – 33.0)	2 (-1.8 – 5.0)	0.343
	Lateral rot. [a]	1	(-0.94 –3.0)	-3	(-5.5 – 3.0)	4 (1.3 – 7.2)	0.005[*]
	Posterior tilt [a]	-9	(-10.6 – -6.6)	-11	(-13.0 – -8.4)	2 (-1.0 – 5.0)	0.182
30-40°	*Internal rot.* [a]	33	(30.4 – 34.8)	31	(28.6 – 33.6)	1 (-1.9 – 4.8)	0.380
	Lateral rot. [a]	3	(1.3 – 5.1)	-1	(-2.8 – 1.5)	4 (1.0 – 6.7)	0.009[*]
	Posterior tilt [a]	-7	(-9.2 – -5.2)	-10	(-11.9 – -7.4)	2 (-0.54 – 5.5)	0.105
40-50°	*Internal rot.* [a]	34	(31.5 – 36.0)	32	(29.6 – 34.9)	2 (-2.0 – 4.8)	0.387
	Lateral rot. [a]	6	(4.0 – 7.9)	2	(-0.4 – 4.1)	4 (1.1 – 7.0)	0.008[*]
	Posterior tilt [a]	-6	(-8.0 – -3.8)	-9	(-11.7 – -6.8)	3 (0.10 – 6.6)	0.043[*]
50-60°	*Internal rot.* [a]	35	(32.5 –37.2)	34	(31.0 – 36.5)	1 (-2.5 – 4.7)	0.533
	Lateral rot. [a]	9	(7.1 – 11.1)	5	(2.4 –7.1)	4 (1.2 – 7.4)	0.007[*]
	Posterior tilt [a]	-5	(-7.4 – -2.8)	-9	(-11.4 – -6.0)	4 (0.08 – 7.2)	0.045[*]
60-70°	*Internal rot.* [a]	36	(33.5 – 38.4)	35	(32.3 – 38.0)	1 (-3.0 – 4.6)	0.674
	Lateral rot. [a]	12	(10.3 – 14.3)	8	(5.7 – 10.3)	4 (1.2 – 7.4)	0.006[*]
	Posterior tilt [a]	-4	(-6.7 – -1.7)	-8	(-11.1 – -5.3)	4 (0.20 – 7.8)	0.040[*]
70-80°	*Internal rot.* [a]	37	(34.2 – 39.5)	37	(33.5 – 39.6)	0 (-3.8 – 4.4)	0.883
	Lateral rot. [a]	16	(13.5 – 17.8)	11	(8.5 – 13.4)	5 (1.4 – 8.0)	0.006[*]
	Posterior tilt [a]	-4	(-6.4 – -0.8)	-8	(-11.1 – -4.7)	4 (0.08 – 8.6)	0.046[*]
80-90°	*Internal rot.* [a]	38	(34.8 – 40.5)	38	(34.6 – 41.2)	0 (-4.7 – 4.0)	0.889
	Lateral rot. [a]	19	(16.6 – 21.1)	14	(11.4 – 16.6)	5 (1.4 –8.3)	0.006[*]
	Posterior tilt [a]	-3	(-5.9 – 0.0)	-8	(-11.1 – -4.3)	5 (0.21 – 9.3)	0.041[*]
90-100°	*Internal rot.* [a]	38	(35.2 – 41.4)	39	(35.8 – 43.0)	-1 (-5.9 –3.6)	0.633
	Lateral rot. [a]	22	(19.1 – 24.0)	17	(13.9 –19.5)	5 (1.2 – 8.5)	0.011[*]
	Posterior tilt [a]	-2	(-5.6 – 0.9)	-7	(-11.1 – -3.7)	5 (0.11 – 9.9)	0.045[*]
100-110°	*Internal rot.* [a]	38	(35.0 – 41.8)	41	(37.0 – 44.7)	-2 (-7.6 – 2.7)	0.343
	Lateral rot. [a]	25	(22.0 – 27.3)	19	(15.9 – 22.0)	6 (1.7 – 9.7)	0.006[*]
	Posterior tilt [a]	-1	(-4.9 – 2.0)	-7	(-11.1 – -3.2)	6 (0.45 – 11.0)	0.034[*]
110-120°	*Internal rot.* [a]	38	(34.2 – 41.7)	42	(37.8 – 46.5)	-4 (-9.9 – 1.5)	0.150
	Lateral rot. [a]	29	(24.9 – 30.8)	21	(17.9 –24.6)	7 (2.1 – 11.1)	0.004[*]
	Posterior tilt [a]	-1	(-4.5 – 3.0)	-7	(-11.1 – -2.5)	6 (0.34 –11.8)	0.038[*]

Analyses of scapulothoracic motion during abduction and forward flexion using a Cardan sequence (Y-X-Z): 1) protraction (i.e. internal rotation) is positive rotation around the thoracic Y-axis; 2) upward rotation is negative rotation around the scapular X'-axis; and 3) posterior tilt is positive rotation around the scapular Z"-axis. Abbreviations: SAPS, Subacromial Pain Syndrome; CI, Confidence Interval; rot, rotation.

[a] Mixed model analysis with fixed effects: humerothoracic elevation angle, group (i.e. SAPS versus control) × humerothoracic elevation angle, plane of elevation, humeral axial rotation and with adjustments for age, sex (male or female) and hand dominancy (yes or no).

[*] Statistically significant difference at $P < 0.05$.

Supplement 5. Difference in glenohumeral motion from initial position

		Abduction		**Forward flexion**	
		SAPS vs. controls		SAPS vs. controls	
		Mean difference (95% CI)	*P value*	*Mean difference (95% CI)*	*P value*
Offset	*Plane* [a]	-6 (-14.5 – 1.9)	0.132	-6 (-13.3 – 1.0)	0.089
	Elevation [a]	-3 (-6.1 – -0.8)	0.012*	-4 (-6.6 –1.1)	0.007*
	Internal rotation [a]	11 (2.4 – 19.8)	0.013*	6 (-3.1 – 14.3)	0.202
30-40°	*Plane* [a]	2 (-3.0 – 6.0)	0.506	5 (0.5 – 10.1)	0.032*
	Elevation [a]	-1 (-1.7 – 0.4)	0.218	0 (-1.9 – 0.9)	0.491
	Internal rotation [a]	-1 (-4.9 – 3.7)	0.780	-6 (-11.4 – -0.7)	0.027*
40-50°	*Plane* [a]	3 (-2.3 – 8.9)	0.244	5 (-0.5 – 10.2)	0.076
	Elevation [a]	-1 (-2.4 – 0.7)	0.286	-1 (-2.6 – 0.4)	0.149
	Internal rotation [a]	-1 (-6.6 – 3.9)	0.618	-6 (-11.2 – 0.2)	0.058
50-60°	*Plane* [a]	4 (-1.8 – 10.5)	0.166	5 (-0.9 – 11.1)	0.096
	Elevation [a]	-1 (-3.0 – 1.1)	0.352	-2 (-3.4 – 0.2)	0.075
	Internal rotation [a]	-1 (-6.8 – 4.6)	0.674	-5 (-11.4 – 0.8)	0.089
60-70°	*Plane* [a]	5 (-1.1 – 12.1)	0.104	5 (-1.6 –11.4)	0.134
	Elevation [a]	-2 (-4.1 – 1.0)	0.224	-2 (-4.4 – -0.4)	0.018*
	Internal rotation [a]	-1 (-7.3 – 4.6)	0.643	-4 (-10.7 – 1.9)	0.171
70-80°	*Plane* [a]	7 (-0.03 – 14.0)	0.051	5 (-1.5 – 12.4)	0.122
	Elevation [a]	-2 (5.2 – 0.8)	0.153	-3 (-5.1 – -0.5)	0.020*
	Internal rotation [a]	-2 (-7.7 – 4.5)	0.599	-4 (-10.4 – 2.5)	0.227
80-90°	*Plane* [a]	9 (1.2 –16.0)	0.024*	6 (-1.3 – 13.3)	0.104
	Elevation [a]	-3 (-6.3 – 0.6)	0.108	-3 (-5.2 – -0.2)	0.035*
	Internal rotation [a]	-2 (-8.4 – 4.2)	0.502	-3 (-9.7 – 3.1)	0.308
90-100°	*Plane* [a]	10 (2.3 – 18.0)	0.012*	7 (-0.8 – 15.0)	0.077
	Elevation [a]	-4 (-7.6 – 0.4)	0.074	-3 (-5.8 – -0.1)	0.043*
	Internal rotation [a]	-3 (-8.9 – 3.7)	0.417	-3 (-9.2 –3.9)	0.423
100-110°	*Plane* [a]	12 (3.3 – 20.0)	0.007*	8 (0.4 –16.9)	0.041*
	Elevation [a]	-4 (-8.5 – 0.3)	0.069	-3 (-6.7 – -0.2)	0.037*
	Internal rotation [a]	-3 (-9.2 – 3.4)	0.362	-2 (-8.7 – 4.3)	0.494
110-120°	*Plane* [a]	13 (4.2 – 21.7)	0.004*	10 (1.8 – 19.4)	0.019*
	Elevation [a]	-5 (-9.8 – -0.3)	0.037*	-4 (-7.5 – -0.1)	0.044*
	Internal rotation [a]	-3 (-9.4 – 3.1)	0.316	-2 (-8.6 – 4.3)	0.501

Glenohumeral motion from initial position at 20°-30°. Analyses of glenohumeral motion during abduction and forward flexion using a Euler sequence (Y-X-Y): 1) GH plane of elevation around the scapular Y-axis; 2) GH elevation is a negative rotation around the rotated humeral X'-axis; and 3) internal GH rotation is a positive rotation around the longitudinal humeral Y"-axis. Abbreviations: SAPS, Subacromial Pain Syndrome; CI, Confidence Interval.

[a] Mixed model analysis with fixed effects: humerothoracic elevation angle, group (i.e. SAPS versus control), group × humerothoracic elevation angle, plane of elevation, humeral axial rotation and with adjustments for age, sex (male or female) and hand dominancy (yes or no).* Statistically significant difference at P < 0.05.

Supplement 6. Difference in scapulothoracic motion from initial position

		Abduction		**Forward flexion**	
		SAPS vs. controls		SAPS vs. controls	
		Mean difference (95% CI)	*P value*	*Mean difference (95% CI)*	*P value*
Offset	*Internal rot.* [a]	0 (-3.8 – 2.8)	0.770	2 (-1.8 – 5.0)	0.343
	Lateral rot. [a]	5 (2.3 – 7.8)	0.001*	4 (1.3 – 7.2)	0.005*
	Posterior tilt [a]	4 (0.7– 6.5)	0.016	2 (-1.0 – 5.0)	0.182
30-40°	*Internal rot.* [a]	0 (-0.9 – 0.3)	0.320	0 (0.8 – 0.5)	0.688
	Lateral rot. [a]	0 (-0.3 – 1.3)	0.232	0 (-1.3 – 0.5)	0.401
	Posterior tilt [a]	0 (-0.4 – 1.1)	0.408	0 (-0.3 – 1.2)	0.236
40-50°	*Internal rot.* [a]	-1 (-2.0 – -0.3)	0.006*	0 (-1.0 – 0.8)	0.808
	Lateral rot. [a]	1 (-0.3 – 2.3)	0.136	0 (-1.3 – 0.9)	0.736
	Posterior tilt [a]	1 (-0.5 – 2.0)	0.223	1 (0.3 – 2.4)	0.01^{5*}
50-60°	*Internal rot.* [a]	-2 (-2.7 – -0.6)	0.002*	0 (-1.6 – 0.6)	0.357
	Lateral rot. [a]	2 (-0.3 – 3.3)	0.094	0 (-1.2 – 1.3)	0.931
	Posterior tilt [a]	1 (-0.3 – 3.0)	0.100	2 (0.1 – 3.1)	0.033*
60-70°	*Internal rot.* [a]	-2 (-3.5 – -0.7)	0.003*	-1 (-2.2 – 0.5)	0.228
	Lateral rot. [a]	2 (-0.3 – 4.1)	0.097	0 (-1.5 – 1.6)	0.952
	Posterior tilt [a]	2 (-0.2 – 3.8)	0.071	2 (0.2 – 3.8)	0.030*
70-80°	*Internal rot.* [a]	-3 (-4.5 – -1.2)	0.001*	-1 (-3.0 – 0.4)	0.126
	Lateral rot. [a]	2 (-0.3 – 5.2)	0.080	0 (-1.5 – 2.4)	0.657
	Posterior tilt [a]	2 (-0.1 – 4.7)	0.057	2 (0.01 – 4.6)	0.049*
80-90°	*Internal rot.* [a]	-4 (-5.9 – -1.8)	<0.001*	-2 (-4.0 – 0.1)	0.066
	Lateral rot. [a]	3 (-0.3 – 6.1)	0.074	1 (-1.7 – 3.0)	0.596
	Posterior tilt [a]	3 (-0.2 – 5.4)	0.068	3 (0.07 – 5.4)	0.045*
90-100°	*Internal rot.* [a]	-5 (-7.3– -2.5)	<0.001*	-3 (-5.2 – -0.3)	0.027*
	Lateral rot. [a]	4 (-0.1 – 7.4)	0.055	1 (-2.1 – 3.4)	0.664
	Posterior tilt [a]	3 (-0.3 – 6.3)	0.070	3 (-0.1 – 6.1)	0.058
100-110°	*Internal rot.* [a]	-6 (-9.0 – -3.0)	<0.001*	-4 (-7.0 – -1.2)	0.007*
	Lateral rot. [a]	4 (-0.1 – 8.3)	0.055	1 (-1.8 – 4.7)	0.385
	Posterior tilt [a]	4 (-0.1 – 7.3)	0.054	4 (0.2 –7.2)	0.041*
110-120°	*Internal rot.* [a]	-7 (-10.3 – -3.5)	<0.001*	-6 (-9.5 – -2.1)	0.002*
	Lateral rot. [a]	4 (-0.2 – 8.9)	0.063	2 (-1.5 – 6.2)	0.224
	Posterior tilt [a]	4 (0.3 – 8.5)	0.036*	4 (-0.03 – 8.1)	0.052

Scapulothoracic motion from initial position at 20°-30°. Analyses of scapulothoracic motion during abduction and forward flexion using a Cardan sequence (Y-X-Z): 1) protraction (i.e. internal rotation) is positive rotation around the thoracic Y-axis; 2) upward rotation is negative rotation around the scapular X'-axis; and 3) posterior tilt is positive rotation around the scapular Z''-axis. Abbreviations: SAPS, Subacromial Pain Syndrome; CI, Confidence Interval; rot, rotation.

[a] Mixed model analysis with fixed effects: humerothoracic elevation angle, group (i.e. SAPS versus control), group × humerothoracic elevation angle, plane of elevation, humeral axial rotation and with adjustments for age, sex (male or female) and hand dominancy (yes or no).

[*] Statistically significant difference at P < 0.05.

Supplement 7. Activation ratio

	SAPS (n=40)			**Controls** (n=30)			**Between-group difference**†	
	n	Median	IQR (25 – 75th)	n	Median	IQR (25 – 75th)	*Z-score*	*P value*
m. trapezius, pars descendens	37	0.67	(0.41–0.90)	26	0.57	(0.28–0.75)	-1.717	0.086
m. trapezius, pars ascendens	37	0.71	(0.52–0.85)	28	0.86	(0.60–0.92)	-1.656	0.098
m. deltoideus, pars clavicularis	40	0.90	(0.76–0.94)	28	0.89	(0.77–0.95)	-0.386	0.699
m. deltoideus, pars acromialis	39	0.84	(0.75–0.94)	29	0.89	(0.80–0.95)	-0.837	0.403
m. deltoideus, pars spinalis	39	0.82	(0.71–0.88)	29	0.88	(0.76–0.92)	-1.531	0.126
m. infraspinatus	29	0.24	(-0.05–0.37)	24	0.19	(0.10–0.36)	-0.268	0.789
m. serratus anterior	34	0.44	(0.33–0.73)	19	0.38	(0.13–0.63)	-1.725	0.085
m. latissimus dorsi	34	0.36	(0.19–0.74)	18	0.43	(0.20–0.66)	-0.019	0.985
m. pectoralis major	39	0.83	(0.70–0.90)	28	0.90	(0.83–0.95)	-2.657	0.008*
m. teres major	38	0.46	(0.26–0.59)	25	-0.02	(-0.16–0.31)	-4.088	<0.001*

Muscle specific agonistic (in-phase) and muscle specific antagonistic (out-phase) measurement of muscle activity using electromyography and expressed as activation ratio (AR). Abbreviations: SAPS, Subacromial Pain Syndrome; n, number; IQR, interquartile range.

† Wilcoxon signed rank test.

* Statistically significant difference ($P < 0.05$).

Supplement 8. Activation Ratio’s expressed as in-phase and out-of-phase EMG signal.