Musculoskeletal Science and Practice 29 (2017) 84–90

Contents lists available at ScienceDirect

Musculoskeletal Science and Practice

journal homepage: https://www.journals.elsevier.com/musculoskeletal-science-and-practice

Original article

Kinematic analysis of the shoulder complex after anatomic and reverse total shoulder arthroplasty: A cross-sectional study

Alexandra Roren [a, b, *], Christelle Nguyen [a, b, d], Clémence Palazzo [a, b, e], Fouad Fayad [f], Michel Revel [a, b], Thomas Gregory [a, g], Serge Poiraudeau [a, b, e, h], Agnès Roby-Brami [b, c], Marie-Martine Lefèvre-Colau [a, b, e]

[a] Paris Descartes University, Sorbonne Paris Cité, Paris, France
[b] Department of Physical Medicine and Rehabilitation, Cochin Hospital, Assistance Publique-Hôpitaux de Paris, Paris, France
[c] Institut des Systèmes Intelligents et de Robotique, Sorbonne University, Pierre et Marie Curie Université, CNRS, UMR 7222, Agathe Team, INSERM, U1150, Paris, France
[d] INSERM UMR 1124, Laboratoire de Pharmacologie, Toxicologie et Signalisation Cellulaire, UFR des Saints-Pères, Paris, France
[e] INSERM UMR 1153, ECaMo Team, Centre de Recherche Épidémiologie et Statistique Sorbonne Paris Cité, Paris, France
[f] Department of Rheumatology, Hôtel-Dieu de France Hospital, Saint-Joseph University, Beirut, Lebanon
[g] Department of Orthopaedic Surgery, European Hospital Georges Pompidou, Assistance Publique-Hôpitaux de Paris, Paris, France
[h] Institut Fédératif de Recherche sur le Handicap, INSERM, Paris, France

A R T I C L E I N F O

Article history:
Received 6 August 2016
Received in revised form 10 March 2017
Accepted 18 March 2017

Keywords:
Total shoulder arthroplasty
Scapula
3D kinematics
Rotation
Translation

A B S T R A C T

Background: The movement of the arm relative to the trunk results from coordinated 3D glenohumeral and scapulothoracic movements. Changes in scapula kinematics may occur after total shoulder arthroplasty and could affect clinical and functional outcomes.
Objectives: To assess the 3D movement of the scapula during arm elevation after anatomic and reverse total shoulder arthroplasty.
Design/Methods: This was a single-centre, non-randomized, controlled cross-sectional study. Patients with anatomic (n = 14) and reverse total shoulder arthroplasty (n = 9) were prospectively enrolled and were compared to age-matched asymptomatic controls (n = 23). 3D scapular kinematics were assessed by a non-invasive, electromagnetic method during arm abduction and flexion. 3D scapular rotations and 3D linear displacements of the barycentre (geometrical centre) at rest and at 30°, 60° and 90° arm elevation; as well as scapulohumeral rhythm were analysed. Participant groups were compared using one-way ANOVA and Bonferroni post-hoc testing for normally distributed data, and Mann–Whitney *U* test for non-normally distributed data.
Results/Findings: Total range of scapular lateral rotation and barycentre displacement were increased, and scapulohumeral rhythm was reduced, in patients with anatomic and reverse total shoulder arthroplasty compared with age-matched controls; however, the global scapular kinematic pattern was preserved.
Conclusion/Interpretation: For patients after total shoulder arthroplasty, the increased contribution of the scapula to arm elevation is consistent with a compensatory mechanism for the reduced glenohumeral mobility. The stability of the global scapula kinematic pattern reflects its mechanical and neuromotor strength.

1. Introduction

Total arthoplasty (TSA) of the glenohumeral (GH) joint is the standard treatment for various end-stage degenerative joint conditions, if conservative treatment fails (Buck et al., 2008; Kim et al., 2011; Sears et al., 2012; Flurin et al., 2013). The usual strategy in the case of primary osteoarthritis is to implant shoulder prosthesis

* Corresponding author. Department of Physical Medicine and Rehabilitation, Cochin Hospital, 27 rue du Faubourg Saint-Jacques, 75014, Paris, France.

E-mail addresses: christelle.nguyen2@aphp.fr (C. Nguyen), clemence.palazzo@aphp.fr (C. Palazzo), fouadfayad@yahoo.fr (F. Fayad), michel.revel@dbmail.com (M. Revel), thomas.gregory@aphp.fr (T. Gregory), serge.poiraudeau@aphp.fr (S. Poiraudeau), agnes.roby-brami@isir.upmc.fr (A. Roby-Brami), marie-martine.lefevre-colau@aphp.fr (M.-M. Lefèvre-Colau).

http://dx.doi.org/10.1016/j.msksp.2017.03.006
2468-7812/

Acronyms

TSA	total shoulder arthoplasty
GH	glenohumeral
aTSA	anatomic shoulder arthoplasty
rTSA	reverse shoulder arthroplasty
HT	humerothoracic
RoM	range of motion
SHR	scapulohumeral rhythm
CS	barycentre of the scapula
F-QuickDASH-D/S score	shortened version of the disabilities of the arm, shoulder and hand outcome measure score

with an anatomic structure (aTSA, whereby a socket replaces the glenoid fossa and a ball replaces the humeral head). Recently, a reverse prosthetic structure (rTSA, with the socket fixed to the humerus and the ball to the glenoid fossa) has been proposed for cases of severe cuff tear, damage of the GH joint due to infection, or complex fractures (Flurin et al., 2013; de Toledo et al., 2012). TSA (whether anatomic or reverse) is generally considered to provide effective pain relief and function. Nevertheless, following TSA, humerothoracic range of motion (HT RoM) remains limited and the factors affecting functional outcomes are still debated, with large inter-individual differences (Magermans et al., 2003; Bergmann et al., 2008; Boileau et al., 2006; Veeger et al., 2006; Wall et al., 2007). A recent study compared patients after aTSA and rTSA showing that pre- and postoperative RoM were larger and pre- and postoperative functional outcome scores were higher for patients with aTSA than rTSA (Flurin et al., 2013). However, active forward flexion, strength and function improved more in patients with rTSA.

The movement of the arm relative to the trunk (HT) results from 3D coordinated movements of the GH and scapulothoracic joints (McClure et al., 2001; Dayanidhi et al., 2005; Fayad et al., 2006; Ludewig et al., 2009). Scapular motion, which is essential for full, functional mobility of the arm, may partly compensate for the loss of GH movement in patients with stiff and painful shoulders (Vermeulen et al., 2002; Rundquist, 2007; Fayad et al., 2008).

Most previous studies investigating shoulder kinematics in TSA have focused on GH RoM, and the measurement of scapula kinematics has been limited to scapulohumeral rhythm (SHR), expressed as a 2D ratio of GH to scapular lateral rotation (Veeger et al., 2006; Kwon et al., 2012; Alta et al., 2014). Only one study has compared 3D scapular rotations in patients after aTSA and rTSA to control subjects (de Toledo et al., 2012). The results showed that SHR was reduced in patients with TSA compared with the controls, suggesting that the scapula contributed more to total shoulder mobility (particularly with rTSA); however, there was no difference in the range of any of the scapular rotations between the patients and controls.

The aim of the present study was to compare scapular motion in patients with aTSA and rTSA to age-matched controls during 2 analytic arm-elevation tasks in the sagittal (flexion) and frontal planes (abduction). In addition to 3D scapula rotations, we also measured the 3D displacement of the barycentre (geometrical centre) of the scapula (CS) to provide a direct and complete measurement of the kinematics of the shoulder complex, including the clavicle (Ludewig et al., 2009; Roren et al., 2015).

Our principal hypothesis was that the contribution of 3D scapular kinematics (3D scapular rotation and 3D displacement of its barycentre) to arm elevation in patients with anatomic or reverse total shoulder arthroplasty would be increased compared to age-matched controls.

2. Methods

2.1. Design

This was a single-centre, non-randomized, controlled, observational study. A convenience sample of 23 patients who had undergone shoulder arthroplasty (14 aTSA and 9 rTSA), and 23 age-matched controls were included between July 2011 and January 2014.

2.2. Patients

Patients had undergone aTSA or rTSA for shoulder osteoarthritis without or with massive rotator cuff tear, respectively. Control subjects were selected from a list of age-matched asymptomatic subjects without clinical or radiological shoulder abnormalities. The time between surgery and assessment was 3–120 months for aTSA and 3–96 months for rTSA (Table 1). None of the participants had any contraindications to active arm elevation or recording with an electromagnetic device.

Demographic, clinical and kinematic data were assessed by the same experimented operator (A.R or F.F) on the same day for each patient or control subject. Patients rated the maximal pain that they had experienced during daily life activities within the last 48 h on a visual analog scale (VAS) (in mm: 0 = no pain, 100 = extreme pain) (Huskisson, 1974). Disability was assessed using the French version of the Constant-Murley Shoulder Outcome Score (Constant and Murley, 1987; Livain et al., 2007) and the short version of the Hand-Disability/Symptom scale (F-QuickDASH-D/S score) (Fayad et al., 2009). Perceived handicap relating to the operated shoulder was measured using a visual analog scale (0–100) (Duruoz et al., 1996; Spacek et al., 2004).

The study protocol was approved by the local institutional review board and all subjects provided informed consent.

2.3. Kinematics analysis

Kinematics analysis was performed as described in (Roren et al., 2012). Briefly, the 3D positions and orientations of the thorax, scapula and humerus were tracked at 30 Hz by 4 Polhemus Fastrak sensors. After preliminary calibration of the bony landmarks, the local coordinate system was computed for each segment, then the joint rotations were expressed in Euler angles according to the protocol of the International Society of Biomechanics (van der Helm, 1997). The study focused on GH and HT rotations, 3D scapular rotations (internal/external, medial/lateral, and anterior/posterior tilt, Fig. 1), 3D positions and 3D displacements of the CS relative to the centre of the thorax (CSx: medial/lateral, CSy: superior/inferior, CSz: anterior/posterior), measured at rest (arms by the sides) and between rest and 30°, 30° and 60° and 60° and 90° of HT elevation. SHR was defined as the ratio of GH RoM to scapular lateral rotation (ML) during a 30° HT elevation (E) from rest to 90° arm elevation: $SHR^E = (GH^E - GH^{E-30})/(ML^E - ML^{E-30})$. Maximum HT and GH elevation was also measured.

Each participant performed 2 successive trials of each task in standing: arm flexion and abduction. Subjects were trained before the recordings and were instructed to avoid moving the trunk and to return to the resting position within 16 s. The two trials were then averaged and the average was used for the statistical analysis.

Table 1
Demographic and clinical characteristics of patients with anatomic (aTSA) and reverse (rTSA) total shoulder arthoplasty and controls with asymptomatic shoulders.

Characteristics			aTSA	rTSA	Controls
			n = 14	n = 9	n = 23
Demographic data		Sex F (%)	71.4	88.9	73.9
		Age (years), mean (SD)	76.2 (7.6)	78.7 (6.9)	75.5 (7.6)
		Time from surgery (months), mean (SD)	34.4 (45.5)	35.2 (37.0)	
		Hand dominance right (%)	100	100	100
Shoulder range of motion (in degrees)	**Flexion**	HT maximal elevation, mean (SD)	**108.0°(29.5)**	**108.7° (16.7)**	**134.8° (10.6)**
		GH maximal elevation, mean (SD)	**67.7° (20.7)**	**71.2° (18.6)**	**89.4° (14.5)**
	Abduction	HT maximal elevation, mean (SD)	**100.0° (27.1)**	**103.2° (16.5)**	**129.8° (18.9)**
		GH maximal elevation, mean (SD)	***59.2° (18.9)***	**66.1° (15.5)**	**88.2° (20.7)**
Perceived handicap,		0–100 mean (SD)	*35.8 (14.0)*	*62.9 (26.2)*	
Pain (VAS)		0-100, mean (SD)	33.6 (27.1)	54.9 (27.2)	
F-QuickDASH-D to S score		0–100, mean (SD)	41.1 (18.4)	51.1 (12.3)	
F-Constant-Murley Shoulder Outcome Score	Pain	0–15, mean (SD)	*12.8 (3.2)*	*8.9 (4.2)*	
	Function	0–20, mean (SD)	14.9 (4.6)	12.3 (4.6)	
	Mobility	0–40, mean (SD)	22.6 (10.6)	19.7 (9.3)	
	Strength	0–25, mean (SD)	7.2 (9.9)	3.0 (2.0)	
	Total	0–100, mean (SD)	46.9 (25.1)	41.3 (20.4)	

Time from surgery: time between surgery and assessment in months. Shoulder range of motion was measured with the electromagnetic device. Maximal pain during daily life activities within the last 48 h on visual analog scale (VAS) in mm (0 = no pain, 100 = extreme pain), F-Constant-Murley Shoulder Outcome Score: French version of the Constant-Murley Shoulder Outcome Score, F-QuickDASH-D/S: French version of the short version of the Disability of the Arm, Shoulder and Hand-Disability/Symptom scale. HT= Humerothoracic, GH = glenohumeral, RoM = range of motion. In bold: significant differences between aTSA or rTSA and controls; In italics: significant differences between aTSA and rTSA, $p < 0.05$.

2.4. Statistical analysis

Demographic, scapular kinematic and clinical (when applicable) variables were described for each group of participants by their means (SD). The Kolmogorov-Smirnov test with the Lilliefors option revealed that overall, the data were normally distributed, except for CS displacement between rest and 30° arm elevation and SHR. Normally distributed data were compared using one-way ANOVA with the factor Group (aTSA, rTSA and control). Bonferroni post-hoc testing was used as appropriate to adjust for multiple pairwise comparisons. A Mann–Whitney *U* test was used to compare CS displacement for the 3 groups (aTSA, rTSA and controls) between rest and 30° arm elevation and SHR. SYSTAT 9 software was used for all analyses and $p < 0.05$ was considered significant.

3. Results

3.1. Demographic characteristics and functional status (Table 1)

Demographic characteristics did not differ significantly between groups (aTSA, rTSA and controls). Perceived handicap was greater in the rTSA group (mean [SD] 62.9/100 [26.2]) than the aTSA group (35.8/100 [14.0], $p = 0.007$) and the Constant subscore for pain was greater in the rTSA (mean 12.8/15 [3.2]) than the aTSA group (8.9/15 [4.2], $p = 0.043$). There were no other statistical differences between aTSA and rTSA.

3.2. Changes in HT and GH RoM (Table 1)

During arm flexion, there were between group differences for HT RoM and GH RoM ($F(2,43) = 10.85$ and $F(2,43) = 7.78$ respectively). Post-Hoc testing showed that HT RoM was lower in patients with aTSA (mean [SD] 108.0° [29.5]) and rTSA (108.7° [16.7]) than controls (134.8° [10.6], $p < 0.01$). GH RoM was also lower in both patients with aTSA (67.7° [20.7]) and rTSA (71.2° [18.6]) than controls (89.4° [14.5], $p < 0.04$).

During arm abduction, between group differences were found for HT RoM and GH RoM ($F(2,43) = 10.39$ and $F(2,43) = 10.86$ respectively). Post-Hoc testing showed that HT RoM was lower in patients with aTSA (100.0° [27.1] and rTSA (103.2° [16.5]) than controls (129.8° [18.9], $p < 0.01$). GH RoM was lower in patients with aTSA (59.2° [18.9] and rTSA (66.1° [15.5] than controls (88.2° [20.7], ($p < 0.01$).

3.3. Changes in 3D scapular kinematics (Figs. 1 and 2)

At rest, the scapula was medially rotated in both patient groups but laterally rotated for controls (Table 2).

Total scapular lateral rotation RoM (from rest to 90°) differed between groups during arm flexion ($F(2,37) = 9.28$) and abduction ($F(2,35) = 8.11$). During arm flexion, it was greater for patients with aTSA (mean [SD] 35.6° [6.7]) and rTSA (27.7° [5.1]) than controls (24.7° [7.7]) but the difference was only significant for patients with aTSA ($p < 0.01$). During arm abduction, it was greater for patients with aTSA (mean [SD] 36.0° [5.6]) and rTSA (31.5° [5.3]) than controls (24.5° [9.0]), but the difference was only significant for patients with aTSA ($p < 0.01$) (Table 2).

Scapular lateral rotation at 30° arm elevation during abduction differed between groups, $F(2,39) = 3.55$. It was decreased in the rTSA group compared to the controls (−1.7° [7.2] and 6.0° [6.9] respectively, $p < 0.04$) (Table 2).

There were also between group differences for CS displacement. During arm flexion, CS displacement differed significantly between groups for 30°–60° and 60°–90° arm elevation ($F(2,42) = 5.61$ and $F(2,39) = 5.29$, respectively). CSz displacement was more anterior for the aTSA than the control group for 30°–60° arm elevation (−1.72 [1.4] versus −0.13 [1.6] cm) and for 60°–90° arm elevation (−2.49 [1.3] versus −1.20 [1.1] cm), $p < 0.01$ (Table 3). CSx displacement from rest to 30° of arm elevation was more lateral for the aTSA (0.79 cm [0.6]) and rTSA groups (2.01 cm [4.8]) than the control group (0.03 cm [1.0], Mann-Whitney, $p < 0.01$).

During arm abduction, CSx displacement for 30°–60° arm elevation differed significantly between groups $F(2,42) = 4.92$. It was more medial for the aTSA compared to the control group (−1.37 [0.7] versus −0.54 [0.8] cm, $p < 0.01$) (Table 3).

Scapular kinematics did not differ significantly between the aTSA and rTSA groups.

3.4. Changes in SHR (Table 4)

During arm flexion, SHR was lower in the patients than the controls. The difference was significant between 30° and 60° of

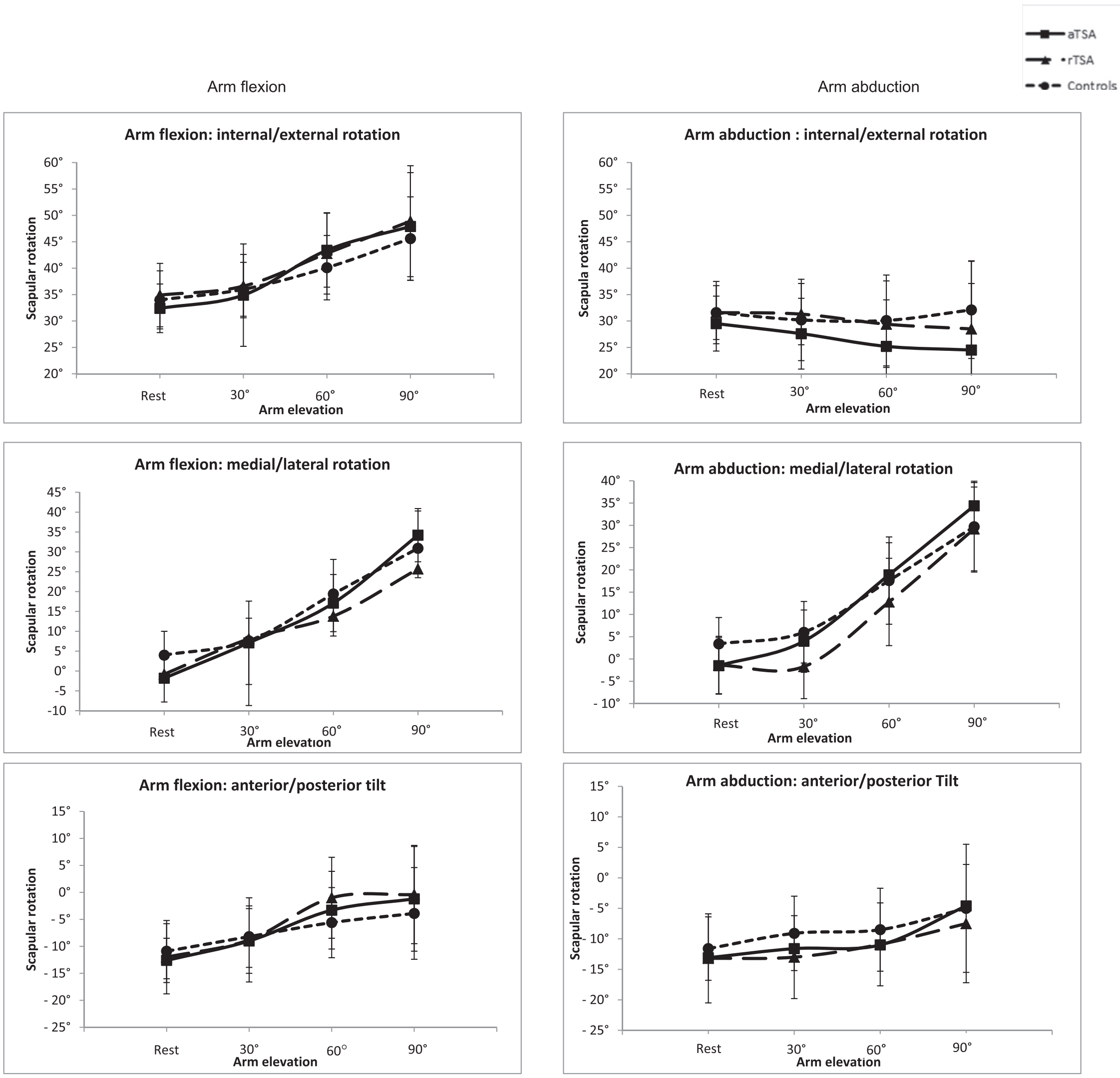

Fig. 1. 3D scapular rotations relative to the centre of the thorax, during arm flexion and arm abduction from rest to 90° arm elevation for patients with anatomic (aTSA) and reverse (rTSA) total shoulder arthroplasty and controls. Medial rotation and anterior tilt are expressed by negative values. Data are mean ± SD.

elevation (aTSA: 1.5 [0.7] and rTSA: 1.9 [0.9] versus controls: 2.2 [1.0]) and between 60° and 90° of elevation, (0.8 [0.5] and 1.1 [0.5] versus 1.7 [0.8]), $p < 0.02$.

During arm abduction, SHR was lower for the patients than the controls. The difference was significant between 30° and 60° of elevation (1.1 [0.7] and 1.4 [0.7] versus 2.4 [1.4]) and between 60° and 90° of elevation (0.8 [0.2] and 0.8 [0.3] versus 2.0 [1.5]), $p < 0.01$.

Global kinematic patterns during planar arm elevation (Figs. 1 and 2).

The graphic representation of the 3D scapular rotations from rest to 90° arm elevation showed the same global kinematic pattern in the 3 groups (aTSA, rTSA and controls): lateral rotation, posterior tilt and internal rotation for arm flexion and (relative) external rotation for arm abduction (Fig. 1).

The graphic representation of the 3D CS displacements (built from 3D CS positions) showed similar kinematic patterns in the 3 groups (aTSA, rTSA and controls) (Fig. 2).

4. Discussion

This is the first study to show changes in 3D scapular rotations and 3D CS displacements in patients with aTSA and rTSA compared with age-matched control subjects. The results showed that scapular lateral rotation RoM was increased between rest and 90°, SHR was decreased between 30° and 90° arm flexion and abduction, and CS displacements were increased in the patient groups. Nevertheless, the amplitude of the differences was small, and the global pattern of scapular rotation kinematics was preserved.

The results showed that GH RoM was significantly lower for both the aTSA and rTSA groups compared with the control group, which corroborates with the results of previous studies (Veeger et al., 2006; de Toledo et al., 2012).

In both patient groups, the scapula was medially rotated at rest. This particular scapular posture has already been described in previous studies that assessed scapular kinematics in patients with aTSA (de Toledo et al., 2012). In the present study, the results for

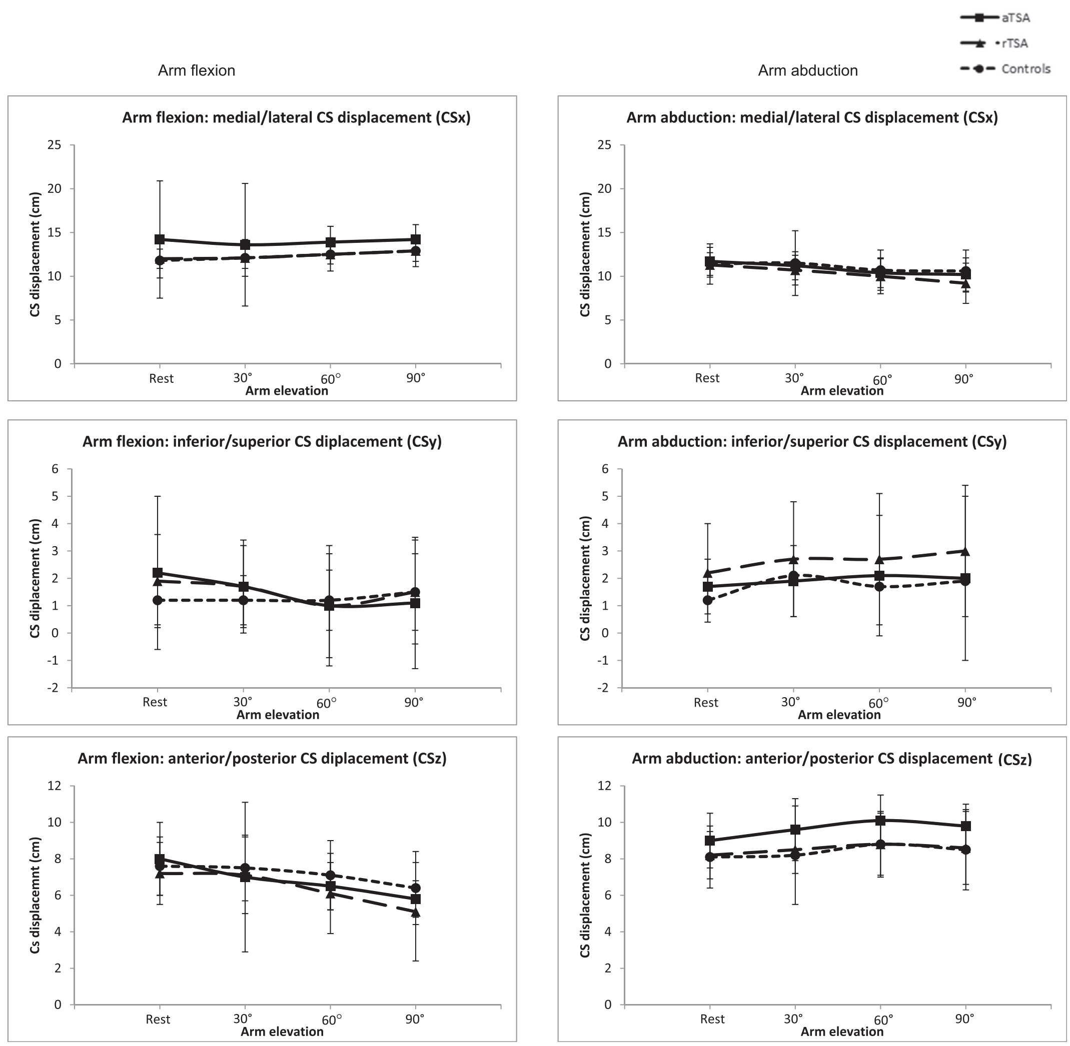

Fig. 2. 3D displacements of the barycentre of the scapula (CS) (built from 3D CS positions), relative to the centre of the thorax, during arm flexion and arm abduction from rest to 90° arm elevation for patients with anatomic (aTSA) and reverse (rTSA) total shoulder arthroplasty and controls. Lateral, superior and posterior CS displacements are expressed by increasing values. Data are mean ± SD.

SHR in asymptomatic shoulders at 30°–90° arm elevation agreed with the findings of previous studies that the scapular lateral rotation contributed to approximately one-third of the active HT elevation (Inman et al., 1996; Ludewig et al., 2009; Scibek and Carcia, 2012). SHR was significantly reduced in both aTSA and rTSA groups, with no difference between groups, which is also in agreement with previous studies (Kwon et al., 2012; de Toledo et al., 2012; Alta et al., 2014). The increase in total scapular lateral rotation RoM, and the decrease in SHR in patients with aTSA and rTSA compared to controls demonstrates the greater contribution of scapular lateral rotation to arm elevation in patients with TSA, as has been shown in many previous studies (Veeger et al., 2006; Mahfouz et al., 2005; Kontaxis and Johnson, 2008; Kwon et al., 2012; de Toledo et al., 2012).

Whether the greater contribution of scapular lateral rotation to arm elevation in TSA patients than controls is due to the pathology or the surgery is unclear. In fact, patients with GH osteoarthritis have been shown to have increased lateral rotation (Fayad et al., 2008), and many studies have shown that massive rotator cuff tears are associated with increased scapular lateral rotation during arm elevation (Graichen et al., 2001; Michener et al., 2003; Mell et al., 2005; Kibler et al., 2013). Increased scapular lateral rotation may therefore reflect a compensatory mechanism by the scapula to maintain arm elevation despite the decrease in GH RoM. The large CS medial/lateral displacements (CSx) found in patients with aTSA and rTSA in the present study could also be interpreted as a compensatory mechanism to maintain arm elevation.

Nevertheless, despite small differences in amplitude during rest to 90° arm elevation, the global kinematic patterns of 3D scapular rotations and 3D CS displacements in relation to the thorax were similar in all 3 groups. The global kinematic patterns of rotations were consistent with those found in many studies of healthy subjects (Meskers et al., 1998; Pascoal et al., 2000; McClure et al., 2001; Borstad and Ludewig, 2002; Fayad et al., 2006; Crosbie et al., 2008; Borstad et al., 2009; Ludewig et al., 2009), as were the RoM and direction of the CS displacements from rest to 90° for arm flexion (mainly lateral (CSx) and anterior (CSz) displacement) and abduction (mainly medial (CSx) displacement) (Roren et al., 2015).

Table 2
3D scapular rotations for aTSA and rTSA patients and controls.

Arm Movement	Scapular rotation (degrees)		aTSA	rTSA	Controls
Flexion	Internal/external rotation	rest	32.4 (4.6)	34.9 (6.0)	34.0 (5.5)
		30°	34.9 (9.7)	36.6 (6.0.)	36.0 (5.1)
		60°	43.4 (7.0)	42.8 (7.7)	40.1 (6.1)
		90°	47.9 (10.2)	48.9 (10.5)	45.6 (7.9)
	Medial/lateral rotation	rest	−1.8 (6.0)	−0.8 (6.5)	4.0 (6.0)
		30°	7.1 (10.5)	8.1 (16.3)	7.6 (5.7)
		60°	17.1 (7.2)	13.8 (10.6)	19.4 (8.7)
		90°	34.2 (6.7)	25.7 (7.4)	30.9 (9.4)
	Total scapular RoM	rest-90°	**35.6 (6.7)**	27.7 (7.1)	**24.7 (7.7)**
	Anterior/posterior tilt	rest	−12.6 (4.1)	−12.0 (6.8)	−10.9 (5.1)
		30°	−9.0 (6.0)	−8.8 (7.8)	−8.2 (5.7)
		60°	−3.3 (7.2)	−1.0 (7.5)	−5.6 (6.5)
		90°	−1.2 (9.7)	−0.4 (9.1)	−3.9 (8.5)
		30°	27.6 (6.7)	31.3 (5.8)	30.2 (7.7)
		60°	25.2 (8.8)	29.4 (8.2)	30.1 (8.6)
		90°	24.5 (12.6)	28.5 (12.9)	32.1 (9.2)
	Medial/lateral rotation	rest	−1.5 (6.3)	−1.4 (6.5)	3.4 (5.9)
		30°	4.0 (7.0)	**−1.7 (7.2)**	**6.0 (6.9)**
		60°	18.9 (7.2)	12.8 (9.8)	17.6 (9.8)
		90°	34.4 (5.2)	29.2 (9.4)	29.7 (10.2)
	Total scapular RoM	rest-90°	**36.0 (5.6)**	31.5 (5.3)	**24.5 (9.0)**
	Anterior/posterior tilt	rest	−13.1 (4.1)	−13.2 (7.3)	−11.6 (5.2)
		30°	−11.6 (6.2)	−13.0 (6.8)	−9.1 (6.1)
		60°	−11.0 (7.4)	−10.9 (6.8)	−8.5 (6.8)
		90°	−4.6 (11.1)	−7.5 (9.7)	−4.9 (10.5)

RoM: range of motion, Medial rotation and anterior tilt are expressed by negative values, In bold: significant difference between aTSA or rTSA and controls, $p < 0.05$.

Furthermore, the 3D scapular rotations and 3D CS displacements in the aTSA, rTSA and control groups well reflected the coupling between scapular rotations and translations (mainly coupling between internal rotation and lateral (CSx) and anterior (CSz) displacement and between posterior tilt and inferior (CSy) displacement), and showed that the fine coordination between scapular and clavicular motion is preserved following TSA (Roren et al., 2015). These findings reflect the mechanical and neuromotor strength of the scapular kinematic pattern, despite reduced HT RoM and radical changes in GH anatomy (reverse relationship between scapular and humeral components).

This study has several limitations. Firstly, the sample was small, however, the controls were age-matched, which rules out the known effect of aging on scapular kinematics (Culham and Peat, 1993; Endo et al., 2001). The standard deviations were often large; nevertheless, intra- and inter-individual variability in scapular kinematics has been reported in several studies (Pascoal et al., 2000; Meskers et al., 2007; Roren et al., 2013). Pain could have interfered with the results for GH range of motion and scapular kinematics (Lawrence et al., 2014a, b), however, it is not possible to isolate the effect of pain from that of other factors linked to pathology and the consequences of surgery (residual peri-articular stiffness, mechanical limits of the prosthesis, proprioceptive impairment etc.). The major limitation is that patients were not assessed before surgery, thus we were not able to differentiate the effects of the pathology from those of the surgery.

Table 3
3D barycentre of scapula (CS) displacement for aTSA and rTSA patients and controls.

Arm movement	CS displacement (cm)		aTSA	rTSA	Controls
Flexion	CSx	rest-30°	**0.79 (0.6)**	**2.01 (4.8)**	**0.03 (1.0)**
		30°–60°	1.41 (0.9)	0.56 (0.7)	1.17 (2.6)
		60°–90°	1.55 (1.2)	0.88 (1.3)	1.0 (1.0)
	CSy	0°–30°	−0.42 (0.7)	−0.20 (0.9)	0.1 (1.0)
		30°–60°	−0.68 (1.5)	−0.94 (0.9)	−0.12 (0.7)
		60°–90°	−0.51 (1.8)	−0.43 (0.8)	0.22 (1.1)
	CSz	rest-30°	−0.35 (0.7)	0.37 (1.3)	0.07 (0.7)
		30°–60°	**−1.72 (1.4)**	−1.14 (0.8)	**−0.13 (1.6)**
		60°–90°	**−2.49 (1.3)**	−1.81 (0.9)	**−1.20 (1.1)**
Abduction	CSx	rest-30°	−0.52 (0.4)	−0.34 (0.3)	−0.59 (0.9)
		30°–60°	**−1.37 (0.7)**	−1.2 (1.1)	**−0.54 (0.8)**
		60°–90°	−1.16 (1.6)	−2.18 (1.2)	−0.74 (1.7)
	CSy	0°–30°	0.19 (0.5)	0.25 (0.2)	0.30 (1.1)
		30°–60°	0.39 (1.5)	0.44 (1.0)	0.34 (1.1)
		60°–90°	0.38 (2.5)	0.19 (1.2)	0.50 (1.7)
	CSz	rest-30°	0.52 (0.8)	0.25 (0.2)	0.41 (0.6)
		30°–60°	1.01 (1.0)	0.82 (0.9)	0.53 (0.8)
		60°–90°	0.67 (1.3)	0.99 (1.5)	0.30 (1.4)

CSx: medial/lateral displacement, CSy: superior/inferior displacement, CSz: anterior/posterior displacement, increasing CS values indicate lateral displacement (CSx), superior displacement (CSy) and posterior displacement (CSz). In bold: significant difference between aTSA or rTSA and controls, $p < 0.01$.

5. Conclusion

In accordance with our hypothesis, the contribution of 3D scapular kinematics to arm elevation was greater in patients with TSA than control subjects, suggesting that the scapula compensates for the loss of GH mobility. Nevertheless, the global pattern of scapular kinematics was preserved, demonstrating the mechanical and neuromotor strength of this pattern. Future studies should compare scapular kinematics before and after arthroplasty to determine whether the change in kinematics is related to the pathology or the surgery.

Table 4
Scapulohumeral rhythm for aTSA and rTSA patients and controls.

Arm elevation	aTSA	rTSA	Controls
Flexion (degree range)			
rest-30°	3.0 (2.2)	1.9 (1.2)	4.2 (5.3)
30°–60°	**1.5 (0.7)**	**1.9 (0.9)**	**2.2 (1.0)**
60°–90°	**0.8 (0.5)**	**1.1 (0.5)**	**1.7 (0.8)**
Abduction (degree range)			
rest-30°	2.2 (2.6)	4.4 (1.6)	4.4 (3.8)
30°–60°	**1.1 (0.7)**	**1.4 (0.7)**	**2.4 (1.4)**
60°–90°	**0.8 (0.2)**	**0.8 (0.3)**	**2.0 (1.5)**

In bold: significant difference between aTSA or rTSA patients and controls, Mann Whitney *U* test, $p < 0.05$.

Acknowledgement

We thank Johanna Robertson for her assistance with the English language.

References

Alta, T.D., de Toledo, J.M., Veeger, H.E., Janssen, T.W., Willems, W.J., 2014. The active and passive kinematic difference between primary reverse and total shoulder prostheses. J. Shoulder Elb. Surg. 23 (9), 1395–1402. http://dx.doi.org/10.1016/j.jse.2014.01.040.

Bergmann, J.H., de Leeuw, M., Janssen, T.W., Veeger, D.H., Willems, W.J., 2008. Contribution of the reverse endoprosthesis to glenohumeral kinematics. Clin. Orthop. Relat. Res. 466 (3), 594–598. http://dx.doi.org/10.1007/s11999-007-0091-5.

Boileau, P., Watkinson, D., Hatzidakis, A.M., Hovorka, I., 2006. Neer Award 2005: the Grammont reverse shoulder prosthesis: results in cuff tear arthritis, fracture sequelae, and revision arthroplasty. J. Shoulder ElbowSurg. 15, 527–540. http://dx.doi.org/10.1016/j.jse.2006.01.003.

Borstad, J.D., Ludewig, P.M., 2002. Comparison of scapular kinematics between elevation and lowering of the arm in the scapular plane. Clin. Biomech. 17, 650–659.

Borstad, J.D., Szucs, K., Navalgund, A., 2009. Scapula kinematic alterations following a modified push-up plus task. Hum. Mov. Sci. 28, 738–751. http://dx.doi.org/10.1016/j.humov.2009.05.002.

Buck, F.M., Jost, B., Hodler, J., 2008. Shoulder arthroplasty. Eur. Radiol. 18 (12), 2937–2948. http://dx.doi.org/10.1007/s00330-008-1093-8.

Constant, C.R., Murley, A.H., 1987. A clinical method of functional assessment of the shoulder. Clin. Orthop. Relat. Res. 214, 160–164.

Crosbie, J., Kilbreath, S.L., Hollmann, L., York, S., 2008. Scapulohumeral rhythm and associated spinal motion. Clin. Biomech. 23, 184–192. http://dx.doi.org/10.1016/j.clinbiomech.2007.09.012.

Culham, E., Peat, M., 1993. Functional anatomy of the shoulder complex. J. Orthop. Sports Phys. Ther. 18, 342–350. http://dx.doi.org/10.2519/jospt.1993.18.1.342.

Dayanidhi, S., Orlin, M., Kozin, S., Duff, S., Karduna, A., 2005. Scapular kinematics during humeral elevation in adults and children. Clin. Biomech. 20, 600–606. http://dx.doi.org/10.1016/j.clinbiomech.2005.03.002.

de Toledo, J.M., Loss, J.F., Janssen, T.W., van der Scheer, J.W., Alta, T.D., Willems, W.J., Veeger, D.H., 2012. Kinematic evaluation of patients with total and reverse shoulder arthroplasty during rehabilitation exercises with different loads. Clin. Biomech. 27 (8), 793–800. http://dx.doi.org/10.1016/j.clinbiomech.2012.04.009.

Duruoz, M.T., Poiraudeau, S., Fermanian, J., Menkes, C.-J., Amor, B., Dougados, M., Revel, M., 1996. Development and validation of a rheumatoid hand functional disability scale that assesses functional handicap. J. Rheumatol. 23, 1167–1172.

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/10.2519/jospt.1993.18.1.342.

Fayad, F., Hoffmann, G., Hanneton, S., Yazbeck, C., Lefevre-Colau, M.M., Poiraudeau, S., Revel, M., Roby-Brami, A., 2006. 3 D scapular kinematics during arm elevation: effect of motion velocity. Clin. Biomech. 21, 932–941.

Fayad, F., Roby-Brami, A., Yazbeck, C., Hanneton, S., Lefevre-Colau, M.M., Gautheron, V., Poiraudeau, S., Revel, M., 2008. Three-dimensional scapular kinematics and scapulohumeral rhythm in patients with glenohumeral osteoarthritis or frozen shoulder. J. Biomech. 41 (2), 326–332.

Fayad, F., Lefevre-Colau, M.M., Gautheron, V., Macé, Y., Fermanian, J., Mayoux-Benhamou, A., Roren, A., Rannou, F., Roby-Brami, A., Revel, M., Poiraudeau, S., 2009. Reliability, validity and responsiveness of the French version of the questionnaire Quick Disability of the Arm, Shoulder and Hand in shoulder disorders. Man. Ther. 14 (2), 206–212. http://dx.doi.org/10.1016/j.math.2008.01.013.

Flurin, P.H., Roche, C.P., Wright, T.W., Marczuk, Y., Zuckerman, J.D., 2013. A comparison and correlation of clinical outcome metrics in anatomic and reverse total shoulder arthroplasty. Bull. Hosp. Jt. Dis. 73 (Suppl. 1), S118–S123.

Graichen, H., Stammberger, T., Bonél, 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 (6), 1192–1198. http://dx.doi.org/10.1016/S0736-0266(01)00035-3.

Huskisson, E.C., 1974. Measurement of pain. Lancet 9 (2), 1127–1131.

Inman, V.T., Saunders, J.B., Abbott, L.C., 1996. Observations of the function of the shoulder joint. 1944. Clin. Orthop. Relat. Res. 330, 3–12.

Kibler, W.B., Ludewig, P.M., McClure, P.W., Michener, L.A., Bak, K., Sciascia, A.D., 2013. Clinical implications of scapular dyskinesis in shoulder injury: the 2013 consensus statement from the « Scapular Summit ». Br. J. Sports Med. 47 (14), 877. http://dx.doi.org/10.1136/bjsports-2013-092425, 85.

Kim, S.H., Wise, B.L., Zhang, Y., Szabo, R.M., 2011. Increasing incidence of shoulder arthroplasty in the United States. J. Bone Jt. Surg. Am. 93 (24), 2249–2254. http://dx.doi.org/10.2106/JBJS.J.01994, 21.

Kontaxis, A., Johnson, G.R., 2008. Adaptation of scapula lateral rotation after reverse anatomy shoulder replacement. Comput. Methods Biomech. Biomed. Eng. 11, 73–80. http://dx.doi.org/10.1080/10255840802296590.

Kwon, Y.W., Pinto, V.J., Yoon, J., Frankle, M.A., Dunning, P.E., Sheikhzadeh, A., 2012. Kinematic analysis of dynamic shoulder motion in patients with reverse total shoulder arthroplasty. J. Shoulder Elb. Surg. 21 (9), 1184–1190. http://dx.doi.org/10.1016/j.jse.2011.07.031.

Lawrence, R.L., Braman, J.P., Laprade, R.F., Ludewig, P.M., 2014a. Comparison of 3-dimensional shoulder complex kinematics in individuals with and without shoulder pain, part1: sternoclavicular, acromioclavicular, and scapulothoracic joints. J. Orthop. Sports Phys. Ther. 44 (9), 636–645. http://dx.doi.org/10.2519/jospt.2014.5339. A1-8.

Lawrence, R.L., Braman, J.P., Staker, J.L., Laprade, R.F., Ludewig, P.M., 2014b. Comparison of 3-dimensional shoulder complex kinematics in individuals with and without shoulder pain, part 2: glenohumeral joint. J. Orthop. Sports Phys. Ther. 44 (9), 646–655. http://dx.doi.org/10.2519/jospt.2014.5556. B1-3.

Livain, T., Pichon, H., Vermeulen, J., Vaillant, J., Saragaglia, D., Poisson, M.F., Monnet, S., 2007. Intra- and interobserver reproducibility of the French version of the Constant-Murley shoulder assessment during rehabilitation after rotator cuff surgery. Rev. Chir. Orthop. Reparatrice Appar. Mot. 93 (2), 142–149.

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 Jt. Surg. Am. 91, 378–389. http://dx.doi.org/10.2106/JBJS.G.01483.

Magermans, D.J., Smits, N.C., Chadwick, E.K., Veeger, D., van der Helm, F.C., Rozing, P.M., 2003. Discriminating factors for functional outcome after shoulder arthroplasty. A critical review of the literature. Acta Orthop. Belg. 69 (2), 127–136.

Mahfouz, M., Nicholson, G., Komistek, R., Hovis, D., Kubo, M., 2005. In vivo determination of the dynamics of normal, rotator cuff-deficient, total, and reverse replacement shoulders. J. Bone Jt. Surg. Am. 87 (Suppl. 2), 107–113. http://dx.doi.org/10.2106/JBJS.E.00483.

McClure, P.W., Michener, L.A., Sennett, B.J., Karduna, A.R., 2001. Direct 3-dimensional measurement of scapular kinematics during dynamic movements in vivo. J. Shoulder Elb. Surg. 10, 269–277. http://dx.doi.org/10.1067/mse.2001.112954.

Mell, A.G., LaScalza, S., Guffey, P., et al., 2005. Effect of rotator cuff pathology on shoulder rhythm. J. Shoulder Elb. Surg. 14, S58–S64. 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.

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 (4), 941–946. http://dx.doi.org/10.1016/j.jbiomech.2006.02.011.

Michener, L.A., McClure, P.W., Karduna, A.R., 2003. Anatomical and biomechanical mechanisms of subacromial impingement syndrome. Clin. Biomech. 18, 369–379.

Pascoal, A.G., van der Helm, F.F., Pezarat Correia, P., Carita, I., 2000. Effects of different arm external loads on the scapulo-humeral rhythm. Clin. Biomech. 15 (Suppl. 1), S21–S24.

Roren, A., Lefevre-Colau, M.M., Roby-Brami, A., Revel, M., Fermanian, J., Gautheron, V., Poiraudeau, S., Fayad, F., 2012. Modified 3D scapular kinematic patterns for activities of daily living in painful shoulders with restricted mobility: a comparison with contralateral unaffected shoulders. J. Biomech. 45 (7), 1305–1311. http://dx.doi.org/10.2519/jospt.2007.2121, 30.

Roren, A., Fayad, F., Roby-Brami, A., Revel, M., Fermanian, J., Poiraudeau, S., Robertson, J., Lefevre-Colau, M.M., 2013. Precision of 3D scapular kinematic measurements for analytic arm movements and activities of daily living. Man. Ther. 18 (6), 473–480. http://dx.doi.org/10.1016/j.math.2013.04.005.

Roren, A., Lefevre-Colau, M.M., Poiraudeau, S., Fayad, F., Pasqui, V., Roby-Brami, A., 2015. A new description of scapulothoracic motion during arm movements in healthy subjects. Man. Ther. 20 (1), 46–55. http://dx.doi.org/10.1016/j.math.2014.06.006.

Rundquist, P.J., 2007. Alterations in scapular Kinematics in subjects with idiopathic loss of shoulder range of motion. J. Orthop. Sports Phys. Ther. 37, 19–25. http://dx.doi.org/10.2519/jospt.2007.2121.

Scibek, J.S., Carcia, C.R., 2012 Jun 18. Assessment of scapulohumeral rhythm for scapular plane shoulder elevation using a modified digital inclinometer. World J. Orthop. 3 (6), 87–94. http://dx.doi.org/10.5312/wjo.v3.i6.87.

Sears, B.W., Johnston, P.S., Ramsey, M.L., Williams, G.R., 2012. Glenoid bone loss in primary total shoulder arthroplasty: evaluation and management. J. Am. Acad. Orthop. Surg. 20 (9), 604–613. http://dx.doi.org/10.5435/JAAOS-20-09-604.

Spacek, E., Poiraudeau, S., Fayad, F., Lefèvre-Colau, M.M., Beaudreuil, J., Rannou, F., Fermanian, J., Revel, M., 2004 May. Disability induced by hand osteoarthritis: are patients with more symptoms at digits 2-5 interphalangeal joints different from those with more symptoms at the base of the thumb? Osteoarthr. Cartil. 12 (5), 366–373.

van der Helm, F.C., 1997. A standardized protocol for motion recordings of the shoulder. In: Proceedings of the First Conference of the ISG.

Veeger, H.E., Magermans, D.J., Nagels, J., Chadwick, E.K., van der Helm, F.C., 2006. A kinematical analysis of the shoulder after arthroplasty during a hair combing task. Clin Biomech. 21 (Suppl. 1), S39–S44. http://dx.doi.org/10.1016/j.clinbiomech.2005.09.012.

Vermeulen, H.M., Stokdijk, M., Eilers, P.H.C., Meskers, C.G.M., Rozing, P.M., Vliet Vlieland, T.P.M., 2002. Measurement of three dimensional shoulder movement patterns with an electromagnetic tracking device in patients with a frozen shoulder. Ann. Rheum. Dis. 61, 115–120.

Wall, B., Nové-Josserand, L., O'Connor, D.P., Edwards, T.B., Walch, G., 2007. Reverse total shoulder arthroplasty: a review of results according to etiology. J. Bone Jt. Surg. Am. 89 (7), 1476–1485. http://dx.doi.org/10.2106/JBJS.F.00666.