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How Do Scapulothoracic Kinematics During Shoulder Elevation Differ Between Adults With and Without Rotator Cuff Arthropathy?

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Abstract

Background Rotator cuff arthropathy with loss of active arm elevation can be successfully treated with nonanatomic reverse total shoulder arthroplasty to restore active elevation. Shoulder kinematics in this context predominantly focus on glenohumeral motion, neglecting scapular motion, although both substantially contribute to global shoulder motion. Because scapular kinematics are difficult to assess clinically and in the laboratory, they are not well understood and therefore are often reduced to glenohumeral models with a static scapula.

Questions/purposes (1) Does the scapulohumeral rhythm (scapular rotation/glenohumeral elevation ratio) change during arm elevation? (2) Is there any scapular motion before arm elevation becomes clinically visible? (3) How do scapulothoracic kinematics during shoulder elevation differ between adults with and without rotator cuff arthropathy?

Methods This was a comparative kinematics study of 20 young adult volunteers (reference group) without rotator cuff impairment (seven females, 13 males; mean age: 27 ± 3.5 years) and 20 patients (22 shoulders) with cuff tear arthropathy (10 females, 10 males; mean age: 74 ± 6.2 years). We used a three-dimensional (3-D) motion analysis system from Vicom with eight high-speed infrared cameras (frame rate 200 Hz) and 25 skin markers. Kinematics were studied for scapulothoracic and glenohumeral movements using the Upper Limb Evaluation in Movement Analysis (ULEMA) open-source model. The main motion studied was active arm elevation in the scapular plane. After data cleaning, modeling, and normalization, changes of scapulohumeral rhythm and scapular motion at the beginning of arm elevation were analyzed qualitatively, and statistical parametric mapping was applied to study the difference in scapulothoracic kinematics between adults with and without rotator cuff arthropathy.

Results The scapular rhythm changes continuously during elevation. Whereas in people without rotator cuff arthropathy, a homogenous proportional relative angular contribution between 85° and 120° could be observed, this regular pattern was disturbed in patients with rotator cuff arthropathy. We observed medial scapular rotation before arm elevation became visible, followed by low lateral or even medial scapular rotation (approximately up to 25°) at

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Each author certifies that his or her institution approved the human protocol for this investigation and that all investigations were conducted in conformity with ethical principles of research.

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the beginning of arm elevation. Patients with rotator cuff arthropathy exhibited more scapulothoracic motion between 50° and 93° of elevation than the reference group.

Conclusions Our study introduces a double-normalized data analysis that allows for a more detailed assessment of complex scapular kinematics in a noninvasive way. Scapulothoracic motion is more complex than previously reported, especially in patients with rotator cuff arthropathy. The scapulohumeral rhythm changes dynamically throughout arm elevation. There is counter-directed scapular rotation because of muscular engagement before clinically visible arm elevation. Compared with the homogenous shoulder kinematics in the reference group, patients with rotator cuff arthropathy show a different pattern with predominantly scapular motion in the range between 50° and 93° of arm elevation.

Clinical Relevance The findings of this study suggest that there is a specific pattern of scapular motion during arm elevation in patients with rotator cuff arthropathy. Our study introduces a new noninvasive method that allows for simultaneous analysis of glenohumeral and scapular kinematics. This will enable to investigators explore whether active arm elevation and the physiological motion pattern can be restored after, for example, reverse total shoulder arthroplasty despite a nonanatomic prosthesis configuration.

Introduction

The increasing use of reverse total shoulder arthroplasty has raised interest in shoulder kinematics, but research is still mainly focused on glenohumeral motion [2]. The design of a reverse total shoulder arthroplasty with inversion of the prosthetic components (that is, a head instead of a cup on the glenoid and a cup instead of a humeral head on the proximal humerus) is substantially different from that of an intact joint or anatomic prosthetic design [4]. Clinically, it appears that with medializing and distalizing the center of rotation, the deltoid muscle can compensate for the loss of motors (rotator cuff), resulting in improved active shoulder elevation and improvement in the Constant scores for pain, activity, mobility and strength [16].

In clinical practice, arm elevation is usually attributed to glenohumeral motion because scapulothoracic motion is difficult to assess clinically and radiologically [9, 19]. However, arm elevation in the scapular plane are composite and coordinated motions of the scapula and humerus relative to the thorax [11]. Mechanically, the glenohumeral joint is a relatively simple ball-and-socket coupling that, due to the shallow glenoid, relies on soft tissue constraints for joint stability. The scapulothoracic joint is not a real joint but a muscular suspension that positions, moves, and stabilizes the scapula. During arm elevation, glenohumeral elevation and scapular rotation may be observed in the scapular plane. The relative contribution of these two movements to arm elevation is called scapulohumeral rhythm, which is calculated as a ratio between glenohumeral elevation and scapular rotation. It ranges from approximately 1.7:1 [17] to 2:1 [7, 15].

Scapulohumeral rhythm values may be determined at distinct points of elevation or at the point of maximal movements of elevation. However, if physiologic points of maximal movement are not restored (such as in a patient with a shoulder pathology) scapulohumeral rhythms might differ [20]. Studies have shown that the scapulohumeral rhythm changes during arm elevation [13, 21]. Therefore, the values for physiologic scapulohumeral rhythm determined in people with full ROM should probably not be used in those with substantially reduced ROM.

In this study, we addressed the following questions regarding shoulder kinematics: (1) Does the scapulohumeral rhythm change during arm elevation? (2) Is there any scapular motion before arm elevation becomes clinically visible? (3) How do scapulothoracic kinematics during shoulder elevation differ between adults with and without rotator cuff arthropathy?

Patients and Methods

This was a comparative kinematics study performed in 20 young adult volunteers (reference group) and 20 patients (22 shoulders) with cuff tear arthropathy (study group). The reference group included seven females and 13 males with a mean (range) age of 27 ± 3.5 years (21 to 33), all of whom were members of our department. The volunteers were examined between April 2015 and September 2015. The exclusion criteria were any previous upper limb pathologic conditions such as fracture or injury and any previous shoulder surgery. The study group included patients with rotator cuff arthropathy scheduled for reverse total shoulder arthroplasty at our institution between March 2015 and March 2019. The exclusion criteria were revision arthroplasty, lesion of the axillary nerve, neuromotor disorders (for example, Parkinson's disease), and elevated risk for drop-out within 2 years. The study group included 10 females and 10 males with a mean age of 73 ± 6.2 years (59 to 86). Our institutional research board approved the study, and all participants provided written informed consent before participation.

All participants in the reference group had full physiologic elevation and flexion, and the mean (range) point of maximal movement for elevation was 174 ± 7.7° (154 to 191). The starting point of elevation depended on the body's constitution and ranged from -1° to 15° (mean 9.6°, ± 3.8°). The point of maximal movement for flexion was 166 ±10.5° (152 to 186). The study group had reduced active elevation of the affected shoulder ($p < 0.001$), with mean point of maximal movement for elevation 102 ± 36° (59 to 164). The starting point of elevation ranged from 5° to 26° (mean 14°, ± 5.2°).

Experimental Setup

We applied a three-dimensional (3-D) motion analysis system (Vicon, Oxford Metrics Ltd., Oxford, UK) with eight high-speed infrared cameras (frame rate 200 Hz). Twenty-five markers mounted on small tripods and cuffs were placed on the participant's shoulders, arms, and trunk (Fig. 1A-B). Kinematics were obtained for the scapula (scapulothoracic motion) and humerus (global humerothoracic motion) using an open-source model (https://github.com/u0078867/ulema-ul-analyzer) incorporating the recommendations of the International Society of Biomechanics [23]. Two main arm motions were recorded: arm elevation in the scapular plane and forward shoulder flexion. However, in this study, we evaluated only arm elevation. The motion analysis was performed bilaterally, and an investigator (RW, NA) demonstrated only the desired rhythm and speed before capturing the data (self-coordinated instead of conducted motion). A detailed description of the experimental setup was published previously [1], and the data analysis workflow (Fig. 1C-F) is described in the section data analysis further below. The following scapular motion components were assessed: scapular rotation, scapular pro/retraction, and scapular tilting (Fig. 2).

Primary and Secondary Study Outcomes

Our primary study outcome was a difference in the contribution of scapula rotation and glenohumeral elevation to global arm elevation between adults with and without rotator cuff arthropathy. We evaluated this by qualitative recognition of motion patterns and statistical parametric mapping.

Our secondary study outcomes were the change of scapulothoracic rhythm during arm elevations and scapular rotation before arm elevation becomes clinically visible. We evaluated them by qualitatively analyzing double normalized motion analysis plots.

Data Analysis

Data analysis included two normalization steps to transform basic output data (Fig. 3A-C) into a form suitable for analysis of relative contribution of glenohumeral and scapulothoracic joint. The first, time normalization, unifies overall length of the motion cycle (Fig. 1D). The second, one-dimensional (1-D) spatial normalization, normalizes the dynamics within one motion cycle and reduces the number of variables needed to be studied (Fig. 1E), making the calculation of relative contributions possible (Fig 1F). Modelling of arm elevation and normalization to 1000 frames (first normalization) per motion cycle were performed using Matlab (MathWorks Inc, Natick, MA, USA) after initial data cleaning. Kinematic data were then exported in .csv file format for further analysis in R (R Foundation for Statistical Computing, Vienna, Austria). We only analyzed upward motion; therefore, vectors were cut at the respective points of maximal elevation. As the second normalization step, we performed 1-D normalization of glenohumeral and scapulothoracic data using arm elevation or flexion as the reference motion (at sectors of 1°; range 0 to 150). This resulted in vectors containing static positions of the scapula relative to the thorax (rotation, pro/retraction, and inclination) and the humerus relative to the scapula (elevation and flexion) at each 1° of reference motion. Finally, positive or negative increments of scapular and humeral motion in each 1° sector of reference motion were calculated to obtain the relative angular contribution (per 1° of reference motion).

Statistical Analysis

Descriptive statistics was performed with R (R Foundation for Statistical Computing). The open source 1-D statistical parametric mapping (SPM) package (SPM1D, www.spm1d.org) in Matlab (R2018b, The Mathworks Inc) was used to compare the relative contribution of scapulothoracic rotation and glenohumeral elevation to global arm elevation. The SPM test equivalent to a t-test was used to compare double-normalized motion analysis data of adults with and without rotator cuff arthropathy. SPM{t} values show the size of the difference relative to variation in data for each 1° of basic motion. The t^* value is the threshold that corresponds to significance level of $\alpha = 0.05$. Unpaired t-test was used to compare maximal arm elevation between the two groups. Significance level was set to 0.05.

Results

Does the Scapulohumeral Rhythm Change During Arm Elevation?

Although the double-normalized cumulative glenohumeral elevation and cumulative scapular rotation appeared to be homogenous in the reference group, the proportions of glenohumeral elevation to scapular rotation changed from

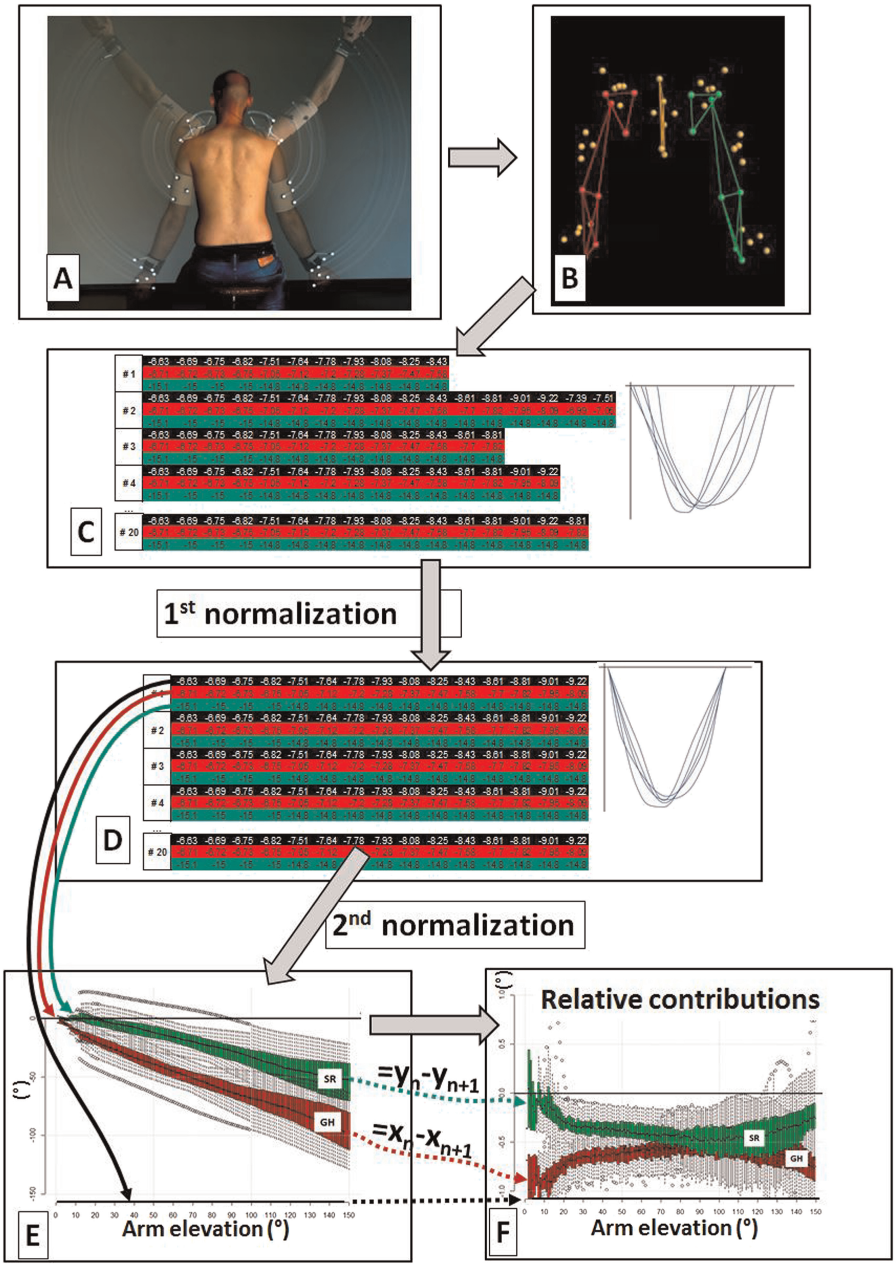

Fig. 1A-F These images show the experimental setup and data analysis (further details and validation of the method may be found here [1]). (**A**) Data were acquired during motion analysis sessions. Reflective skin markers were used to trace the motion. Scapula motion was detected with the cluster marker placed on the acromion. (**B**) This is a screenshot of the computer model created with the Upper Limb Evaluation in Movement Analysis (ULEMA) open-source model. Wire frames represent different segments of the upper limb including the scapula. Orange: thorax, red: left side, green: right side. (**C**) This image shows raw data (degrees) for global arm elevation (black), glenohumeral elevation (red), and scapular rotation (green). The rows have different lengths because each participant may have a different duration of the motion cycle. This is visible in the graphical representation of the raw motion data on the right. (**D**) This image shows that the cycles are synchronized after time normalization to 1000 frames (first normalization). The graphics on the right shows that the starting and ending point are the same for all participants, but the curves may have different dynamics. (**E**) 1-D normalization (second normalization) was performed using global arm elevation (ordinate, black line) as a reference. (**F**) This image shows relative contributions per each 1° of reference motion. A color image accompanies the online version of this article

4:1 at 50° of arm elevation to 3:1 at approximately 80° (Fig. 4A). In the study group, nonhomogenous behavior could be assumed in cumulative graphs (Fig. 4B). When analyzing the relative angular contributions of glenohumeral elevation and scapular rotation per 1° of arm elevation, the pattern was more complex (Fig. 4C). Up to approximately 85° of elevation, the angular contribution of glenohumeral elevation decreased gradually from nearly 1° to 0.5° per 1° of motion. In the same range, the angular contribution of scapular rotation to elevation increased from 0° to 0.5° per 1° of motion. Between 85° and 120° of arm elevation, the angular contribution was homogenous and approximately equal for both components (glenohumeral elevation and scapular rotation). Above 120° the glenohumeral contribution increased, whereas the contribution of scapular rotation appeared to decrease. This observation was not conclusive because the reliability of the model was reduced above 120° due to the skin markers. Throughout the observed elevation range, the contribution of scapular rotation was always lower than that of glenohumeral elevation (curves did not cross). Compared with cumulative graphs for study group (Fig. 4B), the difference in motion pattern becomes clearly visible in relative contribution graphs, showing the pattern of a positive parabola (scapular rotation) or negative parabola (glenohumeral elevation) with two crossing points (Fig. 4D).

Scapular Motion Before Arm Elevation Becomes Clinically Visible

Before any arm elevation was visible, we observed some medial scapular rotation (Fig. 5, between the arrows A and B). At the beginning of arm elevation (approximately up to 10°), lateral scapular rotation was low in the reference group and in some cases even paradoxically medial instead of lateral (one example is presented in Fig. 5, between the arrows B and C). In the study group, this finding was more pronounced and visible up to 20° of elevation (Fig. 4 C-D). In the same ROM, the glenohumeral contribution was higher than 1° to compensate for the opposite (medial) scapular excursion.

Comparing Scapulothoracic Kinematics With and Without Cuff Tear Arthropathy

Patients with rotator cuff arthropathy exhibited more-medial scapula rotation at the beginning of elevation than did participants in the reference group (Figs 4C-D). This was compensated for by increased glenohumeral motion. Furthermore, the motion pattern was biphasic: predominantly glenohumeral motion up to approximately 40°, followed by predominantly scapular rotation up to approximately 115°. Accordingly, there were two relatively distinct crossing points at approximately 40° and 115°. Statistical parametric mapping showed different contributions of glenohumeral elevation and scapular rotation in the range between 50° and 93° of arm elevation (blue shaded range in Figs. 4C-D). In this range of elevation, SPM{t} values exceeded the t* threshold and the corresponding p values were lower than alpha (Fig. 6, gray shaded area).

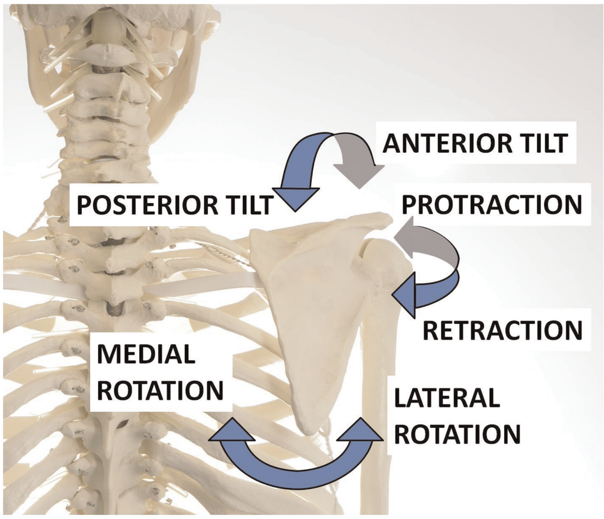

Fig. 2 This photograph shows an overview of three dimensional scapular motion. A color image accompanies the online version of this article

Discussion

Shoulder kinematics in patients with rotator cuff arthropathy predominantly focuses on glenohumeral motion neglecting scapular motion, although both substantially contribute to global shoulder motion. Because scapular kinematics is difficult to assess clinically as well as in the laboratory, it is not well understood. We studied the changes of scapulohumeral rhythm during arm elevation, scapular motion before arm elevation becomes clinically visible, and how scapulothoracic kinematics during arm elevation differs between adults with and without rotator cuff arthropathy. The relative scapular contribution for each 1° of reference motion (elevation) revealed that scapulohumeral rhythm changes dynamically throughout arm elevation and that, compared with the homogenous shoulder kinematics in the reference group, patients with rotator cuff arthropathy show a different pattern with predominantly scapular motion in the range between 50° and 93° of arm elevation.

This study has some limitations. The use of skin markers has been shown to be reliable up to 120° [10, 12, 14, 22]. Therefore, we restricted our calculations and graphical outputs to 150° of elevation and regarded all results above

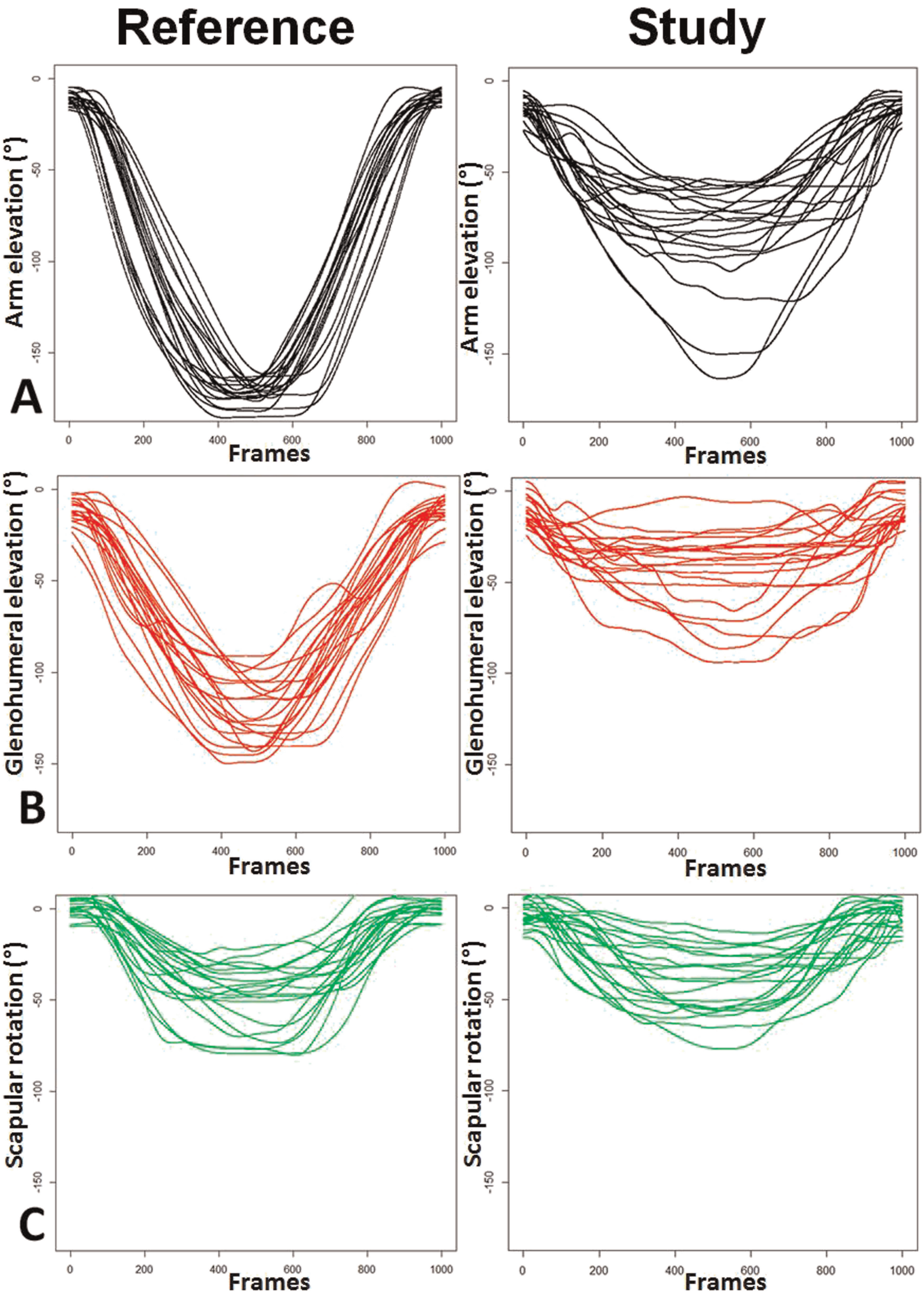

Fig. 3A-C These figures show plots of basic output data of motion analysis for the reference (left) and the study group (right), normalized to 1000 frames (first normalization) for (**A**) arm elevation in the scapular plane, (**B**) glenohumeral elevation, and (**C**) scapular rotation. A color image accompanies the online version of this article.

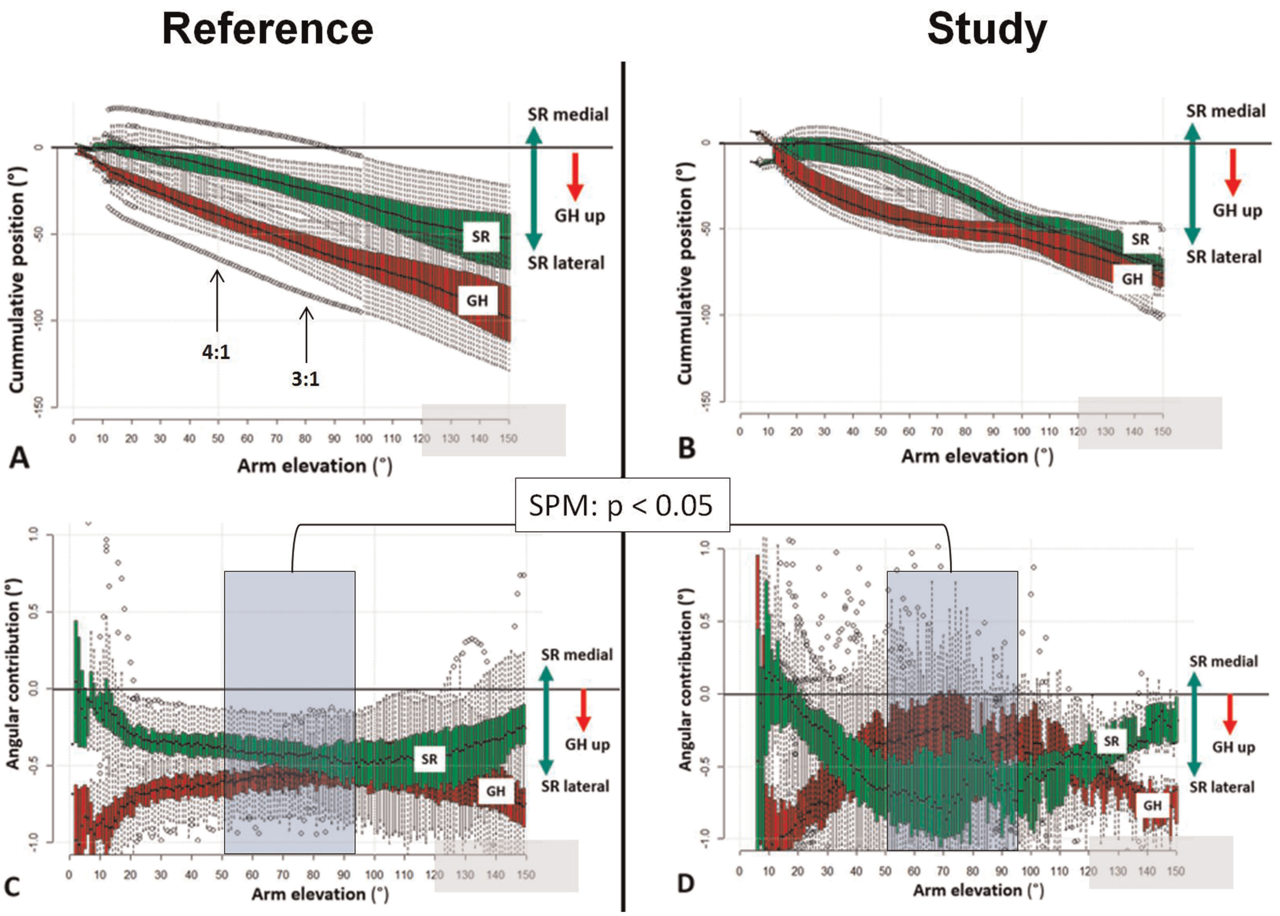

Fig. 4A-D (**A**) This graph shows the cumulative positions of glenohumeral elevation and scapular rotation during global arm elevation in the reference group. For example, in 50° of global arm elevation, glenohumeral elevation contributed approximately 40° and the scapula 10°. (**B**) This graph shows the cumulative positions of glenohumeral elevation and scapular rotation during global arm elevation in the study group. There is a slight but not clearly obvious difference between the study patients and the reference group. (**C**) When analyzing per 1° of global arm elevation, the contributions of glenohumeral elevation and scapular rotation in the reference group differed. For example, between 20° and 21°, the glenohumeral contribution (0.75°) to scapular rotation (0.25°) was 3:1, whereas between 100° and 101°, the glenohumeral contribution (0.5°) to scapular rotation (0.5°) was 1:1. (**D**) This graph shows the relative contribution of glenohumeral elevation and scapular rotation to global arm elevation in patients with rotator cuff arthropathy. The motion pattern is different from that of reference group in the range between 50° and 93° (blue shaded areas, see also Fig. 6). Gray shaded x-scale indicated the region of reduced model reliability due to skin markers; SR = scapular rotation; GH = glenohumeral elevation; SPM = statistical parametric mapping. A color image accompanies the online version of this article.

120° as only suggestive. A further limitation is the focus on concentric motion of the shoulder to reduce the complexity of the topic, potentially missing the differences between eccentric and concentric motion patterns. However, these types of kinematics may be comparable [5, 15], which could be proven or rejected in a separate study implementing our new data analysis method. Another limitation is inherent to the purely kinematic nature of the study; there is no information about motor activity of the shoulder girdle muscles. Finally, the scapular kinematics could be influenced by thorax morphology and posture, which might be different in the patient group with shoulder cuff tear arthropathy than in the younger reference group.

Does the Scapulohumeral Rhythm Change During Arm Elevation?

We showed that the scapulohumeral rhythm is not homogenous during elevation and thus confirmed previous findings that the rhythm can be substantially different in different ranges of elevation [13, 21]. In previous research, the most common pattern of scapulohumeral rhythm was characterized by three separate phases, with the greatest relative amount of scapular rotation occurring between 80° and 140° of arm abduction [3]. Braman et al. [6] found differences in the scapulohumeral rhythm during unconstrained elevation and lowering of the arm in 30° increments between 0° and 120°.

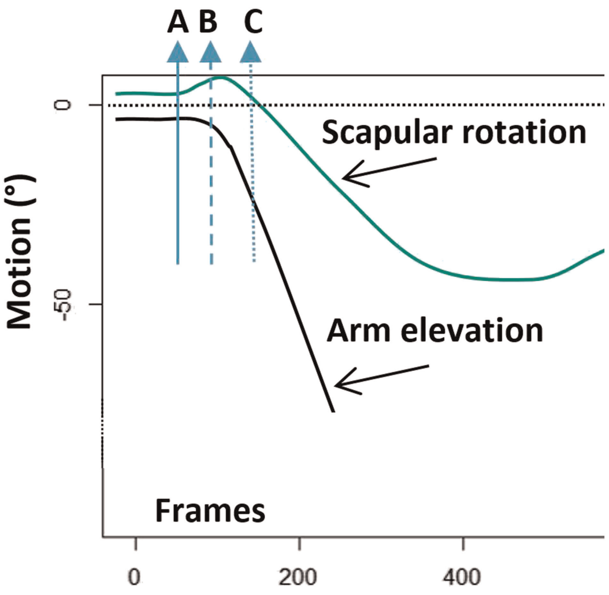

Fig. 5 This graph shows one patient example of scapular rotation (green) and global arm elevation (black) before and at the beginning of arm elevation. Arrow A: Scapular rotation starts but no elevation is visible. Arrow B: Arm elevation starts and the scapula rotates back to its initial position. Arrow C: The scapula is again at its initial position after rotating first medial and then lateral. A color image accompanies the online version of this article.

They found that the scapulohumeral rhythm was highest in the first increment of raising the arm and was higher overall when the arm was lowered. It appears that the complex motion of the scapula cannot be studied adequately using cumulative data because only differentials at 1° of reference motion depict dynamics throughout the studied motion, which is the methodologic advantage of our study. Applying double-normalization of kinematic data, we observed that the scapula "accelerates" in approximately 85° of elevation. Between 85° and 120°, the contribution of the scapula is homogenous and comparable to the contribution of the glenohumeral joint. In the study group, the homogenous proportional contribution between 85° and 120° of abduction was no longer visible. There is an obvious nonlinear curve pattern with two crossing points: the positive parabola for scapular rotation and negative parabola for glenohumeral motion (Fig. 4D). To the best of our knowledge, there are no other studies about the relative contribution of double-normalized data to shoulder kinematics.

Scapular Motion Before Arm Elevation Becomes Clinically Visible

We observed medial scapular rotation instead of the expected lateral scapular rotation, even before any visible arm elevation. This probably reflects an initializing or engaging process of the scapula. The completely relaxed position of the body in the upright position is not equal to the stable position with muscle activation immediately before arm elevation starts. Because the scapula is an intercalated segment suspended only by muscles, its position depends on muscle tension. A relaxed, comfortable posture is only possible with relaxed muscles, but a functional, stable scapular position requires muscle activation, and this

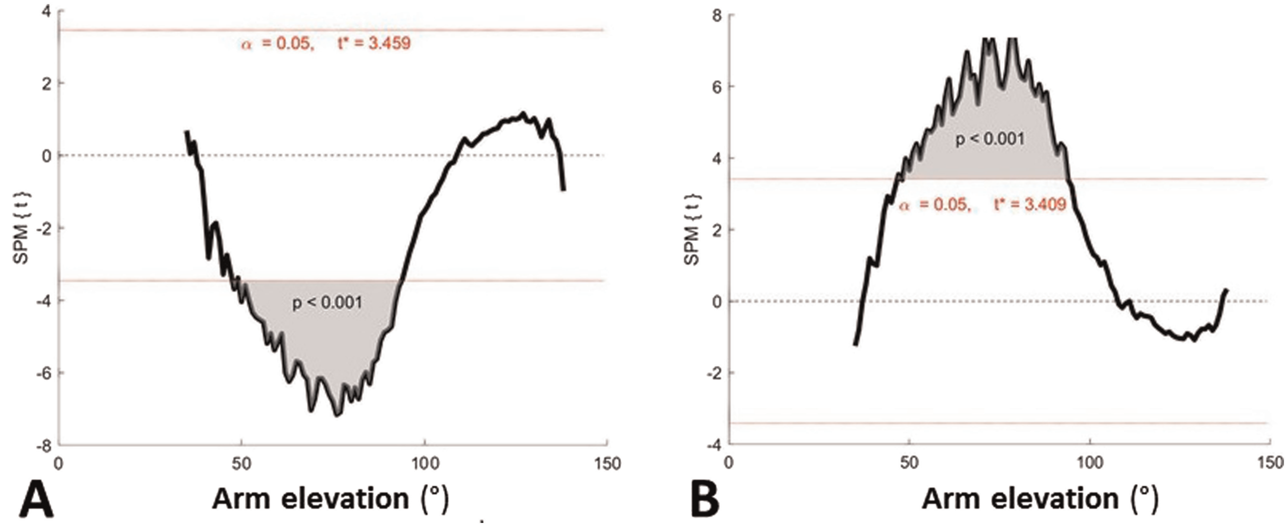

Fig. 6A-B The t-test statistic SPM {t} for difference in relative contribution to arm elevation between adults with and without rotator cuff arthropathy. The critical threshold (red dashed line) of 3.459 and 3.409 for glenohumeral elevation (**A**) and scapular rotation (**B**), respectively, was exceeded with a supra-threshold cluster probability value of $p < 0.001$ indicating a statistically significant difference.

moves the scapula first in the opposite direction (medial rotation) instead of the expected lateral rotation. Muscle activations as alterations in activation amplitude or timing have been identified in participants with shoulder impingement compared with a reference group [18]. For example, in patients with impingement syndrome, there was abnormal muscle recruitment timing [8]. In the study group in our study, the initial medial rotation of the scapula appeared to be more-pronounced than in the reference group. Patients with rotator cuff arthropathy have a loss of tonus and action of torn rotator cuff muscles, resulting in greater initial lateral rotation of the scapula at rest. This could require more "initial stabilizing excursion" for medial scapular rotation instead of the expected lateral scapular rotation. Once the scapula is stabilized, the lateral scapular rotation contributes increasingly to arm elevation.

Comparing Scapulothoracic Kinematics with and Without Cuff Tear Arthropathy

After we applied our new kinematics analysis of relative contribution to double-normalized data, we saw a clear difference in scapulothoracic motion patterns between the reference group without and patients with rotator cuff arthropathy. The main differences are more accentuated initial medial scapula rotation in patients than in reference group, inhomogeneity of relative contributions, and presence of crossing points at approximately 40° and 115°. To the best of our knowledge, there are no comparable studies. Therefore, the next question is: Apart from active arm elevation, does reverse total shoulder arthroplasty also restore the physiologic scapular kinematic pattern?

In conclusion, our study introduces a double-normalized data analysis that allows for a more detailed assessment of complex scapular kinematics in a non-invasive way. Compared with the homogenous scapula kinematics in the reference group, patients with rotator cuff arthropathy show an altered and predominantly scapular motion pattern. Our study will enable a differentiated scapular and glenohumeral kinematic analysis before and after reverse total shoulder arthroplasty exploring whether active arm elevation and the physiological motion pattern can be restored despite a nonanatomic prosthesis.

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