J Shoulder Elbow Surg (2020) 29, 185–194

ELSEVIER

Journal of Shoulder and Elbow Surgery

www.elsevier.com/locate/ymse

Three-dimensional in vivo scapular kinematics and scapulohumeral rhythm: a comparison between active and passive motion

Bonggun Lee, PhD, MD[a], Doosup Kim, PhD, MD[b,*], Younghwan Jang, MD[b], Hanbin Jin, MD[b]

[a]*Department of Orthopedic Surgery, Hanyang University, Seoul, Republic of Korea*
[b]*Department of Orthopedic Surgery, Wonju College of Medicine, Yonsei University, Wonju Severence Christian Hospital, Gangwon, Republic of Korea*

Background: The aim of this study was to compare the scapular kinematics and scapulohumeral rhythm of healthy participants during arm elevation and lowering and to find the difference between active motion and passive motion of the shoulder.
Methods: The study examined the shoulders of 10 healthy men (mean age, 23.5 years; age range, 22-28 years). The shoulders of participants were elevated and lowered while fluoroscopic images were taken, and 3-dimensional bone models were created from 2-dimensional to 3-dimensional images using model registration techniques. The Euler angle sequences of the models' scapular kinematics and scapulohumeral rhythm were compared during active and passive shoulder motion.
Results: There was a significant statistical difference of upward rotation during arm elevation between active and passive shoulder movements ($P = .027$). In particular, the upward rotation between 45° and 90° of elevation showed a statistically significant difference ($P < .001$). When the scapula was tilted posteriorly by active motion, it resulted in a statistically significant difference as there was more tilting in the high-degree range of motions than when it was tilted by passive motion ($P < .001$). There was no statistically significant difference between the 2 groups in scapular external rotation. However, during arm lowering, scapular kinematics did not show statistically significant difference between active and passive motion.
Conclusions: The scapular kinematics showed statistically significant differences between active and passive motion of upward rotation and posterior tilting of the scapula during arm elevation, but there were none during lowering. In terms of upward rotation, active shoulders rotated more upward during arm elevation.
Level of evidence: Basic Science Study; Kinesiology

Keywords: Scapula; humerus; shoulder; range of motion; articular; printing; three-dimensional

Studies have realized that optimal scapular function is a key component of all shoulder function. Furthermore, alterations in scapular position and motion occur in 68% to 100% of patients with shoulder disease and injuries.[26] Specific information about the scapula can help the

Institutional Review Board approval: CR318092.

*Reprint requests: Doosup Kim, PhD, MD, Department of Orthopedic Surgery, Yonsei University, Wonju Severence Christian Hospital, Ilsanro 20, Wonju, Gangwondo 26426, Republic of Korea.

E-mail address: dskim1974@yonsei.ac.kr (D. Kim).

https://doi.org/10.1016/j.jse.2019.05.036

clinician to understand and treat shoulder pain. Thus, understanding of scapular kinematics has become a key to resolve shoulder pain.[4,8,9,11,12,17,22]

Several studies have reported that patients with impingement syndrome tend to have increased anterior tilting of the scapula than patients without it, and abnormal scapular orientation was found to be directly related to the development of the syndrome. In spite of the anatomically abnormal orientation of the scapula, not all cases require positional surgical correction, and conservative treatment is adequate for these patients. Medications and scapular mobilization, including manipulation and specific exercise regimens, constitute conservative management of shoulder pain, with passive and active mobilization being the mainstay of this plan.[9,10,25] However, it is still unknown how these 2 exercise motions affect scapular movement in these patients. In addition, there is no clear comprehension of the different effects of these 2 exercises on scapular movement.[23]

Until now, most cadaveric studies of shoulder kinematics were measured in passive exercise, and there was always a limitation that the measurement of cadaveric study differs from real active motion. It is important to know the difference between active motion and passive motion in in vivo shoulder kinematic studies as it allows better interpretation and understanding.

McQuade and Smidt[18] developed 3-dimensional (3D) measurement techniques using skin-affixed markers and photogrammetry associated with the skin markers moving in relation to bones. Ebaugh et al[5] used an electromagnetic tracking device to record 3D scapulothoracic movement during active and passive arm elevation. There are some discrepancies of methodology between the studies, but both studies used the skin marker for tracking and creating the movement in 3D space. Even though this technique appears to be innovative, the study technique of using skin-affixed markers shows significant inaccuracy in the measurement of the skin markers. On the contrary, 3D-2D model registration employs a 3D assessment technique that makes use of fluoroscopic images. Formerly, the technique was used for 3D kinematic analysis of total knee arthroplasty, but its use has been extended to analyze shoulder kinematics.[15,18] Price et al[23] used 3D measurement techniques to compare scapular motion during active and passive arm motion, but the range of motion tested was limited between 10° and 50°. However, the study did not attempt to measure any kinematic changes in the lowering phase of the arm and measured only changes during active and passive elevation of the arm.

Previous studies investigated scapular kinematics only during arm elevation. However, it is obvious that after elevation of the arm, its lowering must be performed. Furthermore, clinical observations of these movements in individuals with shoulder complaints[1,2,26] and with impingement syndrome[1] demonstrated significant changes in the shoulder kinematics.[1,2,26] In addition, patients with impingement syndrome often experience more pain during lowering of the arms than during elevation.[1-3] Thus, we believe that recording any change in scapular kinematics during the lowering phase of the arm is as important as measuring change in scapular kinematics during the elevation phase of the arm as it is necessary to compare the kinematic changes in both conditions to make a full evaluation of scapular motion and its relation to shoulder pain.

The aim of this study was to compare the scapular kinematics and scapulohumeral rhythm (SHR) of healthy participants during arm elevation and lowering and to find the difference in shoulder kinematics between active motion and passive motion of the shoulder. In this study, we postulated that the shoulder joint would show different kinematics between active motion and passive motion and during elevation and lowering.

Methods

Participants

This study included 10 healthy shoulders from 10 men (mean age, 23.5 years; range, 22-28 years) who had no history of injury or surgery on the shoulders. The radiographic images (Infinix Activ; Toshiba, Tochigi, Japan) were obtained from each participant during elevation of the arm at 30 Hz, starting from the neutral position with the thumbs up to the maximal elevation angle, at a speed of 3 seconds per 1 elevation cycle. The same procedure was done for lowering of the arm. The abduction angle of the arm was maintained throughout the elevation and lowering phases. Examinees had 30-second breaks between each computed tomography (CT) scan (SOMATOM Sensation 16; Siemens Medical Solutions, Malvern, PA, USA). Fluoroscopic images were calibrated to process distortion of the geometric images and the radiographic projection parameters of the object. The obtained CT images had a 1-mm slice pitch (image matrix, 512 × 512; pixel size, 0.9765625 × 0.9765625 mm).

Data image processing

To create 3D models of the humerus and scapula, segmented tomography images and 3D vertical section models were piled up horizontally by ITK-SNAP (Penn Image Computing and Science Laboratory, Philadelphia, PA, USA). In addition, a coordinate system was designated on each model of the humerus and scapula using Geomagic conventions (Geomagic Studio; 3D Systems, Morrisville, NC, USA). Furthermore, the model images coupled with the coordinate system were matched with the silhouette of CT images using JointTrack. The scapular orientation of upward rotation, posterior tilt, and external rotation were plotted along with the data of elevation and lowering of the shoulder using Euler angle sequence. The axis of the scapula was determined according to the International Society of Biomechanics standards. The line connecting the scapular spine and acromial angle, pointing toward the acromial angle, was defined as the Z-axis, and the line pointing forward, perpendicular to the plane formed by the inferior angle, acromial angle, and scapular spine, was defined as the X-axis. The common line perpendicular to the X-axis and Z-axis, pointing upward, was defined as the Y-axis.[27]

The axis of the humerus was determined according to the International Society of Biomechanics standards. The line connecting the glenohumeral rotation center and the midpoint of the lateral epicondyle and medial epicondyle, pointing to glenohumeral rotation center, was defined as the Y-axis, and the line perpendicular to the plane formed by the lateral epicondyle, medial epicondyle, and glenohumeral rotation center, pointing forward, was defined as the X-axis. The common line perpendicular to the Y-axis and X-axis was defined as the Z-axis.[27]

The motion of the scapula was defined as anterior-posterior about the X-axis, internal-external rotation about the Y-axis, and upward-downward rotation about the Z-axis. The scapular kinematic data were interpolated with the best-fitting polynomial function and obtained at each 15° increment. To investigate the tendency of upward rotation, posterior tilt, and external rotation, we found the best-fitted polynomial curve with quadratic or cubic plots by using the moving average method. The scapula's rotational angles were plotted in 15° increments during elevation and lowering of the arm.

Data analysis

Two-way repeated-measures analyses of variance were performed to determine any difference in scapular kinematics along different angles of active and passive elevation of the shoulder. The shoulder was abducted starting from the sitting position, and measurements were recorded at 30°, 45°, 60°, 75°, 90°, 105°, 120°, and maximal abduction angle. Measurement intervals of lowering the arm started from maximal abduction angle and were measured at 120°,105°, 90°, 75°, 60°, 45°, 30°, and resting position. In this study, the dependent variables of interest were internal-external rotation, upward-downward rotation, and anterior-posterior tilt of the scapula and the shoulder's elevation and lowering. Pairwise t-test was used to find a significant interaction. Statistical significance was defined as $P < .05$.

We measured the scapular motion during arm elevation and lowering in active and passive motions. We performed monomial and polynomial regression. The degree of correlation is analyzed through the R^2 value. In regression, the R^2 coefficient of determination is a statistical measure of how well the regression predictions approximate the real data points. An R^2 of 1 indicates that the regression predictions perfectly fit the data.

We measured standard error measurement and minimal detectable changes for analyzing the absolute reliability (Table I).

Table I Standard error measurement (*SEM*) and minimal detectable change (*MDC*) for each scapular rotation

	Upward rotation				Posterior tilt				External rotation			
	Active		Passive		Active		Passive		Active		Passive	
	SEM	MDC	SEM	MDC	SEM	MDC	SEM	MDC	SEM	MDC	SEM	MDC
Start (°)	1.20	3.32	0.54	1.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30°	1.39	3.85	0.58	1.61	0.32	0.89	0.29	0.83	0.37	1.04	0.08	0.23
45°	2.15	5.96	0.78	2.17	0.59	1.65	0.69	1.92	0.60	1.68	0.30	0.83
60°	2.67	7.40	0.83	2.31	0.85	2.37	1.04	2.89	0.64	1.80	0.50	1.40
75°	2.69	7.44	0.87	2.42	0.83	2.31	1.13	3.14	0.63	1.77	0.67	1.87
90°	2.38	6.59	1.04	2.90	0.60	1.68	0.98	2.74	0.70	1.94	0.82	2.27
105°	1.84	5.10	1.12	3.12	0.48	1.33	0.67	1.88	0.86	2.39	0.93	2.58
120°	1.02	2.81	1.04	2.90	0.20	0.57	0.56	1.56	0.86	2.38	0.99	2.75
135[c]	0.41	1.12	1.19	3.31	0.58	1.63	0.75	2.08	0.16	0.44	1.01	2.82
120°	1.25	3.46	1.31	3.63	1.32	3.67	0.86	2.39	0.94	2.62	0.85	2.37
105°	0.79	2.17	1.26	3.50	1.29	3.58	0.98	2.73	0.74	2.01	0.82	2.28
90°	0.69	1.91	1.11	3.09	1.14	3.17	0.91	2.53	0.63	1.75	0.76	2.10
75°	0.84	2.32	1.06	2.94	1.11	3.07	0.68	1.88	0.43	1.21	0.65	1.81
60°	1.08	2.99	1.19	3.30	1.31	3.65	0.48	1.35	0.41	1.14	0.60	1.67
45°	1.10	3.05	1.30	3.61	1.21	3.37	0.48	1.34	0.46	1.27	0.59	1.66
30°	0.90	2.49	1.20	3.35	0.76	2.13	0.46	1.29	0.53	1.47	0.58	1.61
End (°)	1.91	5.29	1.13	3.13	1.29	3.59	0.55	1.53	0.34	0.95	0.65	1.82

Table II The means and standard deviation for each scapular rotation

	Upward rotation		Posterior tilt		External rotation	
	Active	Passive	Active	Passive	Active	Passive
Start (°)	8.2±4.5	4.0±1.9	0	0	0	0
30°	10.9±4.6	5.4±2.0	1.7±0.9	2.4±1.3	1.2±1.6	0.3±0.6
45°	17.3±7.0	8.1±2.7	3.2±1.6	4.3±2.9	2.1±2.5	0.9±2.2
60°	22.6±8.7	11.5±2.9	4.6±2.3	6.4±4.4	2.5±2.7	1.3±3.6
75°	26.4±8.8	15.9±3.0	5.9±2.3	8.9±4.7	2.8±2.6	1.6±4.8
90°	29.2±7.8	21.5±3.6	7.5±1.6	11.3±4.1	3.3±2.9	1.8±5.9
105°	32.3±6.0	28.5±3.9	9.4±1.3	13.5±2.8	4.0±3.6	2.0±6.7
120°	37.5±3.3	37.2±3.6	11.8±0.6	15.2±2.3	4.4±3.5	2.2±7.1
135°	43.8±5.7	47.3±4.1	13.7±2.5	16.2±3.1	4.8±3.3	2.1±7.3
120°	40.6±4.1	41.6±4.5	14.0±3.6	14.0±3.6	5.3±3.9	1.7±6.1
105°	37.1±2.6	35.2±4.3	13.0±3.5	11.4±4.1	3.9±3.0	1.8±5.9
90°	33.0±2.3	29.2±3.8	10.9±3.1	9.3±3.8	3.9±2.6	1.9±5.4
75°	28.4±2.7	23.6±3.6	8.6±3.0	7.7±2.8	4.5±1.8	2.2±4.7
60°	23.3±3.5	18.6±4.1	6.6±3.5	6.4±2.0	5.0±1.7	2.5±4.3
45°	17.7±3.6	14.1±4.5	4.4±3.3	5.0±2.0	5.2±1.9	2.7±4.3
30°	11.7±2.9	10.3±4.1	1.6±2.1	3.2±2.0	5.0±2.2	2.9±4.2
End (°)	6.6±6.3	7.8±3.9	−1.6±3.5	0.5±2.3	3.4±1.4	2.8±4.7

Results

Measurements showed that the mean upward rotation and posterior tilting angles of the scapula increased as participants raised the arm. Lowering the arm resulted in a decrease of these angles. However, the mean external rotation angle of the scapula did not show a statistically significant pattern (Table II). The change in scapular kinematics during elevation had a statistically significant difference when the active and passive motion groups were compared. On the contrary, no significant difference was evident in changes of scapular kinematics between the 2 groups during lowering of the arm.

Values of scapular angles during elevation

During abduction of the arm in the scapular plane, an increment of abduction angle had a significant effect on the upward rotation angle of the scapula ($P < .001$). In addition, there was also a significant difference of change in the upward rotation angle between the active and passive shoulder motion groups ($P = .001$; mean difference, 3.92; 95% confidence interval [CI], 1.81-6.03). The change in mean upward rotation angle during active abduction to the maximal angle was higher than the change found during passive abduction of the shoulder (43.3° ± 4.47° vs. 39.7° ± 6.81°).

The scapula's upward rotation angulations changed more at 45°, 60°, 75°, and 90° in active motion than in passive motion of the shoulder. At these angles, the difference between the 2 groups was 9° to 11°, and this had statistical significance (Fig. 1).

The raised shoulder abduction angles had significant effects on the posterior tilt of the scapula, and the change in posterior tilting angles in accordance with the change in abduction angle had statistical significance ($P < .001$) for both groups. The mean changes in the posterior tilting angles from resting to maximum abduction for active and passive motion groups were 15.1° ± 2.24° and 16.1° ± 3.12°, respectively. It was not statistically significant ($P = .2332$; mean difference, −1.19; 95% CI, −2.12 to −0.27). However, the scapula's posterior tiling angulations changed more at 90°, 105°, and 120° in active motion than in passive motion of the shoulder. There were differences of 3° to 4° between the 2 groups at these angles, and these differences had statistical significances (90°: $P < .048$ [mean difference, −3.84; 95% CI, −7.89 to 0.20]; 105°: $P < .043$ [mean difference, −4.11; 95% CI, −8.00 to −0.22]; 120°: $P < .032$ [mean difference, −3.34; 95% CI, −6.22 to −0.47]; Fig. 2).

The mean changes in external rotation angles for active and passive shoulders were 2.1° ± 7.28° and −2.6° ± 0.94°, respectively (Fig. 3). The changes in external rotation angle on abduction of the shoulder did not have a significant difference ($P = .895$; mean difference, 1.43; 95% CI, 0.82-2.04), and no statistical difference of changes in external rotation angle was evident between the 2 groups ($P = .071$).

Values of scapular angles during lowering

The change in upward rotation angle of the scapula in relation to the shoulder abduction angles had significant effects for both active and passive motion groups ($P < .001$), but no significance was found between the 2 groups on lowering of the arms. The mean change (39.5° ± 8.35°) in the upward rotation angle during active lowering of the shoulder was similar to the mean change (39.5° ± 5.74°) found in passive lowering of the shoulder, and no statistical

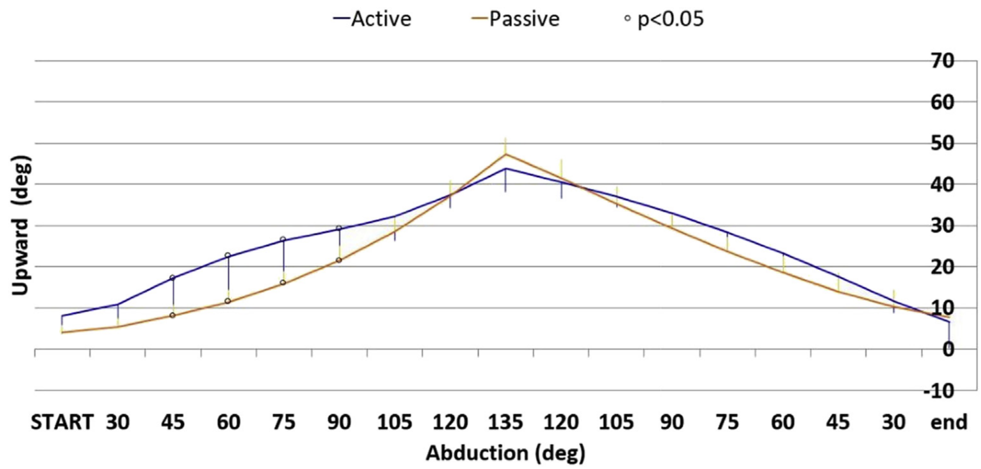

Figure 1 Upward rotation.

significance was found between these changes (P = .139; mean difference, 1.61; 95% CI, −0.65 to 3.88). Change in posterior tilt angles in relation to the abduction angle of the arm had statistically significant difference ($P < .001$). However, no significant difference was found when these changes in active and passive motion groups were compared (P = .612; mean difference, −0.27; 95% CI, −1.45 to 0.91). The mean differences in posterior tilting for active and passive shoulders during lowering of the shoulder were 15.4° ± 2.99° and 15.6° ± 4.89°, respectively.

During the lowering phase, the mean changes in the scapula's external rotation for active and passive shoulders were 1.9° ± 4.12° and 1.1° ± 2.45°, respectively. The changes in external rotation of the scapula in relation to shoulder abduction angle did not have significant effects (P = .326). When the differences between the 2 groups (active and passive shoulder movements) were compared, they did not show statistical difference (P = .077; mean difference, 2.28; 95% CI, 1.67-2.89).

SHR

The mean SHRs for active and passive motion groups during elevation were 3.5 ± 0.17 and 4.1 ± 2.14, respectively. No significant difference was found in SHRs measured during elevation of the shoulder between active motion and passive motion (P = .620; mean difference, 2.14; 95% CI, −7.42 to 11.70). The mean SHRs of active and passive motions in lowering of the shoulder were 3.3 ± 0.30 and 3.3 ± 1.11, respectively, and the difference between the 2 groups showed no significant difference (P = .583; mean difference, 0.31; 95% CI, −0.92 to 1.54).

The SHR of passive elevation measured in the early ranges of abduction was higher than in active motion of the shoulder. The SHR decreased gradually as the shoulder was raised passively, but it remained constant during lowering of the shoulder. Significant difference was found in SHRs measured only during elevation of the shoulder at 30° (Fig. 4).

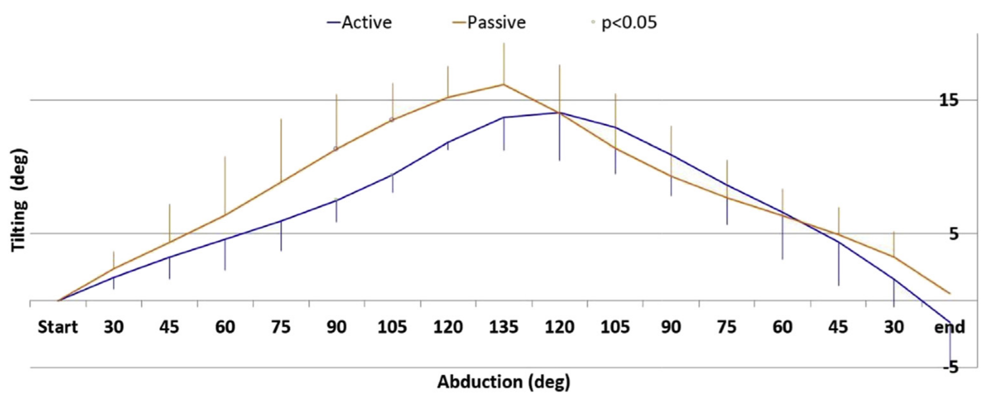

Figure 2 Posterior tilt.

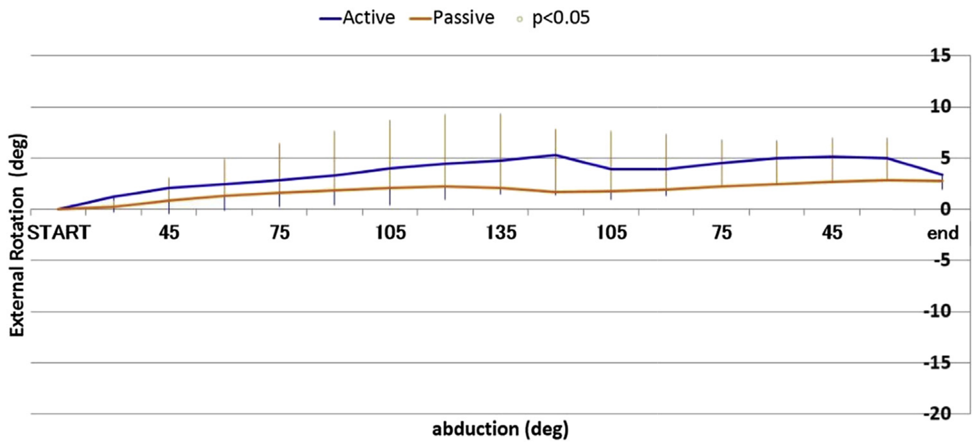

Figure 3 External rotation.

Comparison of R^2 between elevation and lowering of the shoulder

A nonlinear relation between upward rotation angle of the scapula and shoulder abduction angle was shown during the arm elevation phase. As shown in Figure 5, we performed linear curve fits with R^2 values on the data to describe the relationship. The linear R^2 value of the scapular upward rotation angle during elevation was 0.9840 for active motion and 0.9370 for passive motion. However, the R^2 value for the second-order polynomial curve was 0.9836 for active motion and 0.9995 for passive motion. On lowering of the shoulder, the R^2 value for the linear curve was 0.9874 for active motion and 0.9951 for passive motion. Furthermore, the R^2 value for the second-order polynomial curve during lowering was 0.9991 for active motion and 0.9986 for passive motion. As shown in Figure 6, the R^2 values of both active and passive motions during lowering showed a more linear curve than the curve drawn for arm elevation. However, the passive motion of the shoulder during elevation showed a significant change in the rate of scapular upward rotation angle. On the contrary, a more linear relation was evident in active lowering movement of the shoulder.

Linear and polynomial curve fit was also performed to find the relationship between scapular posterior tilting and shoulder elevation. R^2 values of the linear line of best fit for the scapular posterior tilting measured during elevation of the shoulder were 0.9480 for active motion and 0.9943 for passive motion. However, the R^2 value of the second-order polynomial curve was 0.9815 for active motion and 0.9968 for passive motion. During lowering of the shoulder, the monomial and polynomial R^2 values for active motion were 0.9897 and 0.9976, respectively. The monomial and polynomial R^2 values for passive motion were 0.9892 and 0.9920, respectively (Fig. 6).

Discussion

This study investigated the changes in scapular kinematics in relation to active and passive movements of the shoulder. Although previous studies focused on finding changes in scapular kinematics during elevation of the shoulder only, our study has dealt with measuring scapular kinematic changes during lowering of the shoulder as well. We separately measured the change in scapular kinematics in accordance with active and passive motions

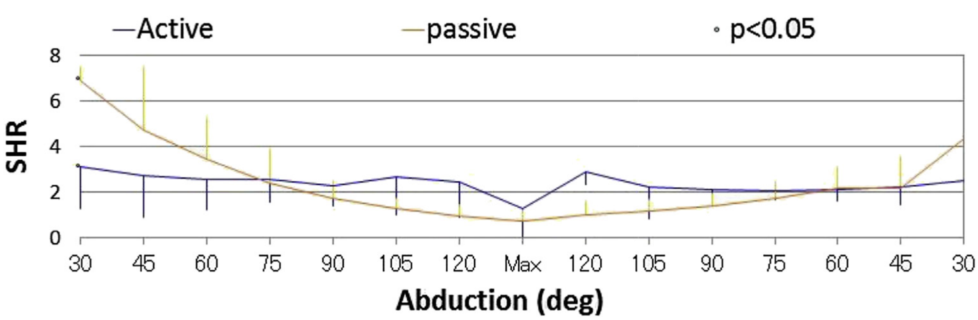

Figure 4 Scapulohumeral rhythm (*SHR*).

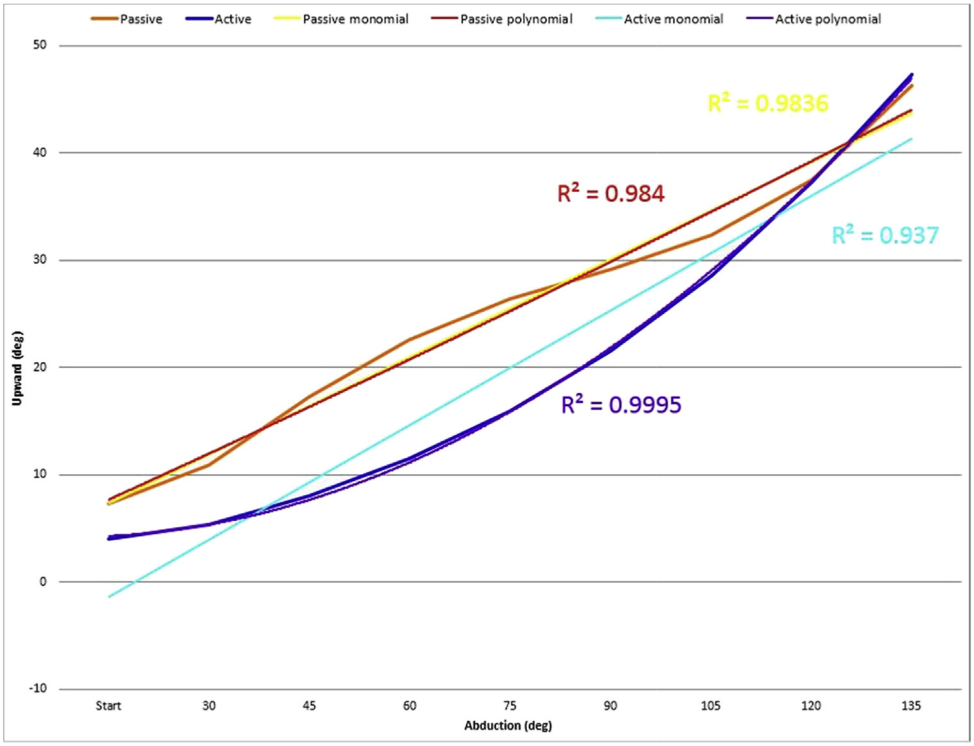

Figure 5 R^2 comparison between active and passive motion in upward rotation angle of scapula during elevation.

of the shoulder and made a comparison of the changes between these 2 groups. Previous studies used electromyography or magnetic sensor landmarks to obtain data of the scapular kinematics. The data from electromyography or magnetic sensors were attached to the skin, which is much more elastic than the bones that were supposed to be the actual targets of the sensors while moving.[8,12] To eliminate or minimize this error of unwanted dislodgment from the anticipated targets, Ludewig et al[13] inserted percutaneous pins with fiducial markers attached directly to the bones, but the invasive nature of this method limits its routine use in live participants. Thus, the accuracy and usefulness of these methods to obtain scapular kinematics are less compared with the 3D-2D bone model registration technique that we used.[15] The bone model registration technique showed 6 degrees of freedom for scapular and humerus kinematics, and it was found that the kinematics measured were similar to the actual bone movements.[17]

The scapular upward rotation angles with both active motion and passive motion showed gradual increase during elevation of the shoulder. Ebaugh et al[5] reported a difference of 4° to 5° in scapular upward rotation angles that was similar to our result. Our study revealed statistical significance of changes in scapular kinematics between active and passive motion groups, but the clinical importance of a 4° to 5° difference was not yet comprehended. Ludewig and Cook[12] and Lukasiewicz et al[14] discovered that shoulders with impingement and rotator cuff disease[6,16] had a decreased scapular upward rotation angle of 4° to 5° than the angle in normal healthy shoulders. Although the discrepancy is small, this small change in upward rotation of the scapula makes a difference between healthy and pathologic shoulders. Thus, we believe that the different scapular kinematics between active and passive motion groups may have some significant effect on the shoulder in clinical and experimental settings. Previous studies have proposed that decreased upward rotation of the scapula can contribute to the development of subacromial impingement syndrome by reducing the size of the subacromial space.[9,12,20] Therefore, we think that passive motion may affect shoulder impingement syndrome rather than active motion. These findings would suggest that exercise, which usually begins passively after rotator cuff repair, can cause impingement. However, because there are many instances of acromioplasty and a coracoclavicular ligament release procedure combined during rotator cuff repair, the possibility of impingement is reduced, and a few passive exercises a day will have little clinical effect. However, the risk of impingement may increase in working with arms in the middle range (such as standing up and working at a computer). Overall, the scapula showed more rotation in active motion than in passive motion. The scapula's rotational changes between active and passive motion groups represented a significant difference in the midrange

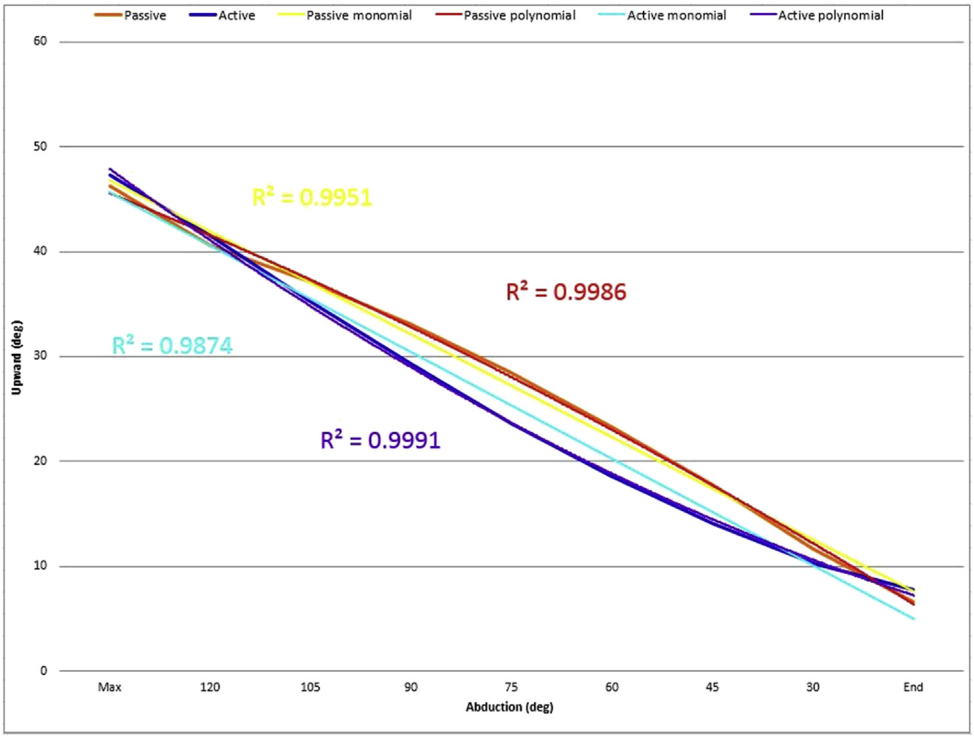

Figure 6 R^2 comparison between active and passive motion in upward rotation angle of scapula during lowering.

of 45° to 90°. No statistical significance was shown in early (resting position to 45°) and late phases (90° to maximal elevation angle), but more upward rotation was found in the active motion group than in the passive motion group in all ranges of arm elevation. The study of Ebaugh et al[5] showed a comparable pattern to ours. Their study had significant inactive upward rotation motion of the scapula between 60° and 90°, and no significance was found between active and passive motion groups in other ranges of shoulder elevation. However, the changes in upward rotation during active motion were generally higher than the changes found in passive motion, as in our study. The significant difference found in their study was between 60° and 90°, and this range was slightly different from ours, which was 45° to 90°. We believe that the discrepancy of the ranges with statistical significance originates from similar but different starting points defined by each author.[18,19] On the other hand, McQuade and Smidt[18] found that in the first phase of arm raising, active motion resulted in higher upward rotation of the scapula, whereas upward rotation of the scapula, in the final two phases, was more affected by passive motion than by active motion.[18] Their pattern was not similar to our pattern, and Ebaugh et al[5] stated that the dissimilarity was the result of variations in performing passive motion. In the actual setting, complete passive motion is somewhat impossible in vivo in performing passive arm elevation with the same repetitive method as during some voluntary or involuntary motion. Thus, we provided enough resting time between tests for the examinees to relax as completely as possible before passive elevation of the shoulder during these intervals.

Unlike the results found during arm elevation, changes in upward rotation of the scapula did not have statistical significance between active and passive motion groups. Both groups were shown to have a gradual curve during arm lowering. Several authors have used SHR to study the characteristics of scapular upward rotation.[15,17] In our study, overall SHR in the 2 groups was obtained and compared to find any different characteristics in upward rotation of the active and passive groups. The overall SHRs in active motion were 3.45 during elevation and 3.31 for lowering. For passive motion, overall SHRs were 4.06 for elevation and 3.33 for lowering. No statistical significance was evident between active and passive motions for overall SHR measured in both arm elevation and lowering. However, the difference in SHR between active motion and passive motion was found to be much higher in raising the arm than in lowering (SHR in elevation, 0.61; SHR in lowering, 0.02). The data (larger SHR value in passive elevation) showed that passive shoulder motion has a smaller effect on scapulothoracic joint motion during elevation. In addition, there is no significant difference in the changes found from both groups in lowering of the arm.

We also performed linear and polynomial curve fit in both elevation and lowering of the shoulder to find a relationship between scapular upward rotation and shoulder abduction angle. As seen in Figures 5 and 6, scapular upward rotation for the linear line of best fit during elevation was 0.9370 for active and 0.9836 for passive shoulder motion. The R^2 value for the second-order polynomial curve was 0.9840 for active motion and 0.9995 for passive motion. The passive motion during arm elevation showed nearly similar R^2 values between linear and polynomial curves, meaning that the scapular upward rotation for the passive motion rotated steadily and linearly. The active motion during arm elevation displayed different R^2 values for both linear and polynomial curves, meaning that the scapular upward rotation for the active motion rotated with changes in abduction angles. During lowering of the shoulder, the R^2 value for active motion was 0.9874 for linear and 0.9991 for polynomial, and the R^2 value for passive motion was 0.9951 for linear and 0.9986 for polynomial.

With these calculations, we explained that both active and passive motions during lowering of the arm cause steady and linear upward rotation of the scapula. The passive motion also represented the general linear relation of the scapular upward rotation to the shoulder abduction angle during both elevation and lowering. Like the linear relation of the different scapular motions to changes in shoulder elevation, SHR during active shoulder motion resulted in constant changes, whereas SHR in passive motion had different rates of change in scapular upward rotation.

The scapula's posterior tilting angle measured in both active and passive motions during elevation of the arm showed gradual increase in its entire cycle of abduction. When data from these 2 motions were compared, elevation in passive motion had posterior tilting of the scapula an average of 2° more than in active motion. The difference of the tilt angle between active motion and passive motion was significant in the higher range of 90° to 120° shoulder abduction. Within the elevation angle of 90° to 120°, passive motion resulted in 4° more tilting than the angle found in active motion. However, no significant difference was evident in tilt angle changes between the 2 groups during lowering. Although it is not clear why elevation and lowering resulted in tilting angles that had dissimilar statistical consequence, we believe that the extent of glenohumeral joint capsule tightness and individual variation of bony morphology in addition to the muscles surrounding the shoulder joint cause the distinctive changes in scapular posterior tilt angles in active and passive motion. The inclusion criteria for the study were all men and the dominant side of the shoulder. If this study included women and the nondominant side of the shoulder, the results may have been different. In addition, the clinical significance of 2° to 4° difference in scapular kinematics must to be confirmed in the future. It has generally been accepted that patients with impingement syndrome have reduced posterior tilting angle of the scapula. Because passive motion exercises are recommended to patients who have undergone surgery for impingement syndrome, further studies should include the effect of passive motion that results in more posterior tilting of the scapula to these patients. On the other hand, previous studies have shown that scapular upward rotation contributes to the subacromial space, which in turn can lead to shoulder impingement syndrome. In our study, more upward rotation of the scapula during arm elevation was observed in active motion than in passive motion. Therefore, this suggests that passive arm elevation is related to shoulder impingement syndrome.

The passive motion during elevation showed nearly similar R^2 values between monomial (0.9943) and polynomial (0.9968) curves, meaning that steady and linear rotation of scapular posterior tilting angles was present in passive motion. Scapular posterior tilting angle in active motion during arm elevation displayed different R^2 values between monomial (0.9480) and polynomial (0.9815) curves, meaning that abduction angle is a dependent change in rotation of scapular posterior tilting.

There was steady and linear tilting of the scapula in both motions during lowering. The same inquiry for passive motion represented linear increase in tilting for both elevation and lowering of the shoulder. However, active motion showed varied rates of the changes in posterior tilting during elevation and steady increase during lowering of the arm. External rotation of the scapula was observed with active abduction of the shoulder during elevation of the arm; internal rotation of the scapula was observed during passive motion. Although it is not easy to explain this phenomenon on the basis of our study, some authors suggested that during active motion, activation of the anterior serratus muscle caused the scapula to rotate externally. In addition, the main reason for internally rotated direction of the scapula during passive motion was the result of ligaments and capsules around the glenohumeral joint pulling the scapula downward with medial shift without activating the anterior serratus muscle above a certain level.[7,21,24]

Three muscles, the upper and lower trapezius and anterior serratus muscles, affect scapular kinematics, and these muscles are the key components in orientation of the scapula during motion. However, the importance, if there is any, of other neighboring muscles and ligaments (eg, the pectoralis minor and coracoclavicular ligament) has not been examined; future studies on these surrounding soft tissues are necessary for more understanding of scapular kinematics.

There are several limitations in this study. First, all participants in our study were young men between 22 and 28 years old. Caution is required in interpretation of our data and application to the general population because sex and age are important factors that influence scapular kinematics. Second, tests were performed on the participants' dominant shoulder only. The gathered data may indicate a different trend in scapular kinematics when the same examination is performed on nondominant shoulders.[15] In the future, we plan to perform the same examination on the nondominant side of the shoulder, and the result will be compared with the scapular kinematics we found in dominant shoulders once we obtain the data. Third, all examinations were performed with patients in the sitting position. We believe that the different postures of examinees may result in slightly different kinematics of the scapula. Last, it was difficult to control and to maintain the exact position of the arm during active motion for each participant, and these minor deviations may have some effect on the final data of scapular kinematics. However, despite the variations, we believe that the data obtained are concrete.

Conclusion

On testing of active and passive motions in both elevation and lowering of the arm, results showed significant changes in upward rotation and posterior tilting of the scapula. During elevation, scapular upward rotation and posterior tilting showed different movement patterns between active and passive motions of the shoulder. No value of scapular kinematics showed statistical significance between active and passive motion groups during lowering of the shoulder.

Disclaimer

The authors, their immediate families, and any research foundations with which they are affiliated have not received any financial payments or other benefits from any commercial entity related to the subject of this article.

References

1. Borstad JD, Ludewig PM. Comparison of scapular kinematics between elevation and lowering of the arm in the scapular plane. Clin Biomech (Bristol, Avon) 2002;17:650-9. https://doi.org/10.1016/S0268-0033(02)00136-5
2. Boublik M, Hawkins RJ. Clinical examination of the shoulder complex. J Orthop Sports Phys Ther 1993;18:379-85.
3. de Morais Faria CD, Teixeira-Salmela LF, de Paula Goulart FR, de Souza Moraes GF. Scapular muscular activity with shoulder impingement syndrome during lowering of the arms. Clin J Sport Med 2008;18:130-6. https://doi.org/10.1097/JSM.0b013e318160c05d
4. Doody SG, Freedman L, Waterland JC. Shoulder movements during abduction in the scapular plane. Arch Phys Med Rehabil 1970;51:595-604.
5. Ebaugh DD, McClure PW, Karduna AR. Three-dimensional scapulothoracic motion during active and passive arm elevation. Clin Biomech (Bristol, Avon) 2005;20:700-9. https://doi.org/10.1016/j.clinbiomech.2005.03.008
6. Graichen H, Stammberger T, Bonel H, Wiedemann E, Englmeier KH, Reiser M, et al. Three-dimensional analysis of shoulder girdle and supraspinatus motion patterns in patients with impingement syndrome. J Orthop Res 2001;19:1192-8.
7. Inman VT, Saunders JB, Abbott LC. Observations of the function of the shoulder joint. 1944. Clin Orthop Relat Res 1996;330:3-12.
8. Karduna AR, McClure PW, Michener LA, Sennett B. Dynamic measurements of three-dimensional scapular kinematics: a validation study. J Biomech Eng 2001;123:184-90.
9. Kibler WB, McMullen J. Scapular dyskinesis and its relation to shoulder pain. J Am Acad Orthop Surg 2003;11:142-51.
10. Kibler WB, Sciascia A. Current concepts: scapular dyskinesis. Br J Sports Med 2010;44:300-5. https://doi.org/10.1136/bjsm.2009.058834
11. Kibler WB, Sciascia A, Wilkes T. Scapular dyskinesis and its relation to shoulder injury. J Am Acad Orthop Surg 2012;20:364-72. https://doi.org/10.5435/JAAOS-20-06-364
12. Ludewig PM, Cook TM. Alterations in shoulder kinematics and associated muscle activity in people with symptoms of shoulder impingement. Phys Ther 2000;80:276-91.
13. Ludewig PM, Cook TM, Shields RK. Comparison of surface sensor and bone-fixed measurement of humeral motion. J Appl Biomech 2002;18:163-70. https://doi.org/10.1123/jab.18.2.163
14. Lukasiewicz AC, McClure P, Michener L, Pratt N, Sennett B. Comparison of 3-dimensional scapular position and orientation between subjects with and without shoulder impingement. J Orthop Sports Phys Ther 1999;29:574-86.
15. Matsuki K, Matsuki KO, Mu S, Yamaguchi S, Ochiai N, Sasho T, et al. In vivo 3-dimensional analysis of scapular kinematics: comparison of dominant and nondominant shoulders. J Shoulder Elbow Surg 2011;20:659-65. https://doi.org/10.1016/j.jse.2010.09.012
16. McClure PW, Michener LA, Karduna AR. Shoulder function and 3-dimensional scapular kinematics in people with and without shoulder impingement syndrome. Phys Ther 2006;86:1075-90. https://doi.org/10.1093/ptj/86.8.1075
17. McClure PW, Michener LA, Sennett BJ, Karduna AR. Direct 3-dimensional measurement of scapular kinematics during dynamic movements in vivo. J Shoulder Elbow Surg 2001;10:269-77.
18. McQuade KJ, Smidt GL. Dynamic scapulohumeral rhythm: the effects of external resistance during elevation of the arm in the scapular plane. J Orthop Sports Phys Ther 1998;27:125-33.
19. Meskers CG, Vermeulen HM, De Groot JH, Van der Helm FC, Rozing PM. 3D shoulder position measurements using a six-degree-of-freedom electromagnetic tracking device. Clin Biomech (Bristol, Avon) 1998;13:280-92.
20. Michener LA, McClure PW, Karduna AR. Anatomical and biomechanical mechanisms of subacromial impingement syndrome. Clin Biomech (Bristol, Avon) 2003;18:369-79. https://doi.org/10.1016/S0268-0033(03)00047-0
21. Perry J. Normal upper extremity kinesiology. Phys Ther 1978;58:265-78.
22. Poppen NK, Walker PS. Normal and abnormal motion of the shoulder. J Bone Joint Surg Am 1976;58:195-201.
23. Price CI, Franklin P, Rodgers H, Curless RH, Johnson GR. Active and passive scapulohumeral movement in healthy persons: a comparison. Arch Phys Med Rehabil 2000;81:28-31.
24. Uhl TL, Kibler WB, Gecewich B, Tripp BL. Evaluation of clinical assessment methods for scapular dyskinesis. Arthroscopy 2009;25:1240-8. https://doi.org/10.1016/j.arthro.2009.06.007
25. van der Heijden GJ, van der Windt DA, de Winter AF. Physiotherapy for patients with soft tissue shoulder disorders: a systematic review of randomised clinical trials. BMJ 1997;315:25-30.
26. Warner JJ, Micheli LJ, Arslanian LE, Kennedy J, Kennedy R. Scapulothoracic motion in normal shoulders and shoulders with glenohumeral instability and impingement syndrome. A study using Moire topographic analysis. Clin Orthop Relat Res 1992;285:191-9.
27. Wu G, van der Helm FC, Veeger HE, Makhsous M, Van Roy P, Anglin C, et al. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion—Part II: shoulder, elbow, wrist and hand. J Biomech 2005;38:981-92. https://doi.org/10.1016/j.jbiomech.2004.05.042