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BASIC SCIENCE

Different scapular kinematics in healthy subjects during arm elevation and lowering: Glenohumeral and scapulothoracic patterns

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Hypothesis: The scapulothoracic (ST) joint affects glenohumeral (GH) joint function. We observed 3-dimensional scapular motions during arm elevation and lowering to identify the scapulohumeral rhythm in healthy subjects and to compare it between the dominant and nondominant arms.
Materials and methods: Twenty-one healthy subjects participated in this study. Participants randomly elevated and lowered the arms in the scapular plane, and data were recorded by a computerized 3-dimensional motion analyzer at each 10° increment.
Results: Of the 42 shoulders, 21 showed a greater ratio of GH motion relative to ST motion whereas the other 21 showed a smaller ratio of GH motion relative to ST motion. The angle of upward rotation of the scapula showed a statistically significant difference between both types. The mean maximum angles of upward rotation, posterior tilting, and internal rotation were 36.2° ± 7.0°, 38.7° ± 5.7°, and 36.8° ± 12.2°, respectively. No significant difference was found in angles of 3 scapular rotations between the dominant and nondominant arms.
Discussion: These results indicate that there are 2 distinctly different scapulohumeral rhythms in healthy subjects but without a significant difference between dominant and nondominant arms. These findings should be referred to when one is interpreting kinematics in a variety of shoulder disorders.
Level of evidence: Basic Science Study.

Keywords: Shoulder motion; scapular kinematics; 3-dimensional motion analyzer

Elevation of the arm for overhead activities is accomplished by combined motion of the sternoclavicular, acromioclavicular, scapulothoracic (ST), and glenohumeral (GH) joints. Because the ST movement is a summation of sternoclavicular and acromioclavicular motion, elevation of

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the arm can be divided into ST and GH components. Cathcart[4] was the first author to recognize the ST contribution to normal shoulder complex kinematics. Codman[5] termed this synchronous motion as scapulohumeral rhythm (SHR). The SHR—the ratio of GH to ST motion—has been a simple and reasonable reflection of dynamic motion of the shoulder complex. Inman et al[11] reported that the SHR was 2:1. Since that time, much research on shoulder kinematics has been directed toward the study of the SHR, and most of it is limited to 2-dimensional studies of scapular upward rotation around an axis perpendicular to the plane of the scapula during humeral elevation.[1,11,18]

Scapular motion is known to occur in other planes.[13,15,16,22] Poppen and Walker[18] described a twisting (tilting) movement of the scapula occurring in combination with upward rotation. Other authors, using magnetic tracking devices or magnetic resonance imaging, have reported terms of upward rotation, posterior tilting (tipping or twisting), and internal rotation (protraction) to describe scapular motion; thus, a variety of terms have been used to define scapular motion.[2,3,6,7,13,15,16,21,22] In this study scapular motions are described in 3 planes: upward and downward rotation in the scapular plane, anterior and posterior tilting in the sagittal plane, and internal and external rotation in the transverse plane.[13]

Recently, clinicians and investigators have focused increased attention on the role of the scapula, alterations in scapular position, and/or scapular dyskinesis.[12,23] Alterations in the resting scapular position and dynamic scapular motion have been frequently recognized in association with many types of shoulder disorders, such as impingement, instability, rotator cuff tears, and frozen shoulder.[12] One study showed that the motion of upward rotation was significantly increased in a group with full-thickness rotator cuff tears compared with that in a control group in forward and scapular plane elevation.[17] Warner et al[23] showed abnormal static or dynamic scapular patterns in 18% of asymptomatic subjects compared with 64% and 100% in the instability and impingement groups, respectively. Compared with normal subjects, those with impingement were shown to exhibit a significantly lower posterior tilting angle of the scapula and a higher superior-inferior scapula position with maximum arm elevation.[13,14] An increased scapular component has been generally accepted to contribute to the SHR in subjects with frozen shoulder.[20]

Scapular motion affects GH joint function during arm elevation, yet little is known about this dynamic normal activity. Moreover, we have little information on whether there are different motion patterns of the ST joint or whether scapular kinematics are the same among subjects and between left and right arms. Inman et al[11] used the term ‘‘the setting phase’’ for the early phase of shoulder motion over the range of 0° to 60° of abduction, indicating preparatory stabilization of the scapula to permit controlled humeral motion. The SHR was generally greatest (less scapular motion) in the setting phase and then decreased beyond 60° of abduction (more scapular motion), and the SHR increased again under 60° of lowering.[24] We assume that muscular stabilization of the scapula increases while raising the arms; thus, less scapular motion would be seen at the setting phase. The setting phase was also reported as the most highly irregular SHR between each subject.[11] We hypothesized that the SHR of some subjects would not be in a constant 2:1 ratio but would decrease (more scapular movement, ST type) or, in contrast, would increase (less scapular movement, GH type) in the setting phase. We also hypothesized that these 2 types would be found at the end range of lowering. The purpose of this study was 2-fold: (1) to measure the 3 scapular motions during arm elevation and lowering and (2) to investigate whether scapular motion is identical among healthy subjects from the initial phase of elevation through the terminal phase of lowering.

Materials and methods

Subjects

The participants in this study were 21 college students (17 men and 4 women) with a mean age of 23.7 years (range, 18-32 years). The mean values (± SD) for height and weight were 169 ± 8 cm and 66.0 ± 14.1 kg, respectively. According to self-report, the dominant arm was the right arm in 19 subjects and the left in 2. None of the participants had had shoulder pain or a medical history of shoulder disorders; one of the authors verified that they did not have instability, restriction in range of motion, scoliosis, or asymmetry of the thoracic cage. Approval was obtained from the internal review board of our institution, and all subjects read and signed a consent form before participation in this study.

Experimental protocol

Scapular rotational motion was measured with a computerized 3-dimensional (3D) motion analyzer (MAC 3D System; Motion Analysis, Santa Rosa, CA). This system was composed of 6 synchronized infrared cameras placed circumferentially, and closely, around the subject being examined and allowed for 50-Hz data capture. Before performing this study, we estimated error due to skin slippage by measuring the distances between bony landmarks and marker locations of the scapula using radiographs. We performed cineradiography of each subject with the marker setting on each bony landmark during the starting and terminal positions and decided individually the proper position of each marker at the coracoid process, acromial angle, and scapular spine. With the subject's chest wall and both arms, iliac crests, and knees being exposed, the following points were bilaterally set up with the smallest-sized reflecting markers (diameter, 0.9 cm; Motion Analysis): the coracoid process, the acromial angle, the base of the scapular spine, the medial and lateral epicondyles of the humerus, and the spinous processes of the second (T2) and seventh (T7) thoracic vertebrae and fifth lumbar vertebra (L5). In each subject, the marker for the inferior angle of the scapula was stuck at 5 positions at regular intervals, because of the large amount of skin slippage that occurred from the start of elevation to maximum

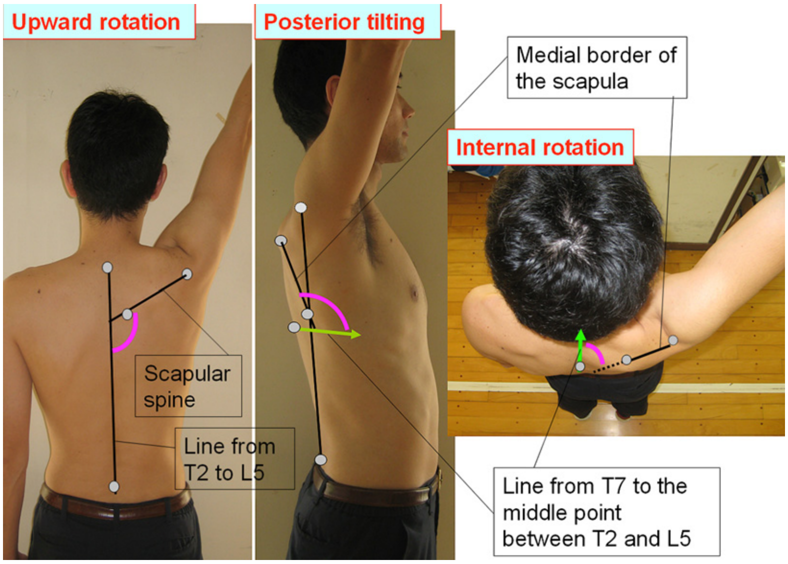

Figure 1 Angle setting. The angle of upward rotation was calculated from the angle between the scapular spine and the line from T2 to L5; the angle of posterior tilting was calculated from the angle between the line connecting the base of the scapular spine and the inferior angle of the scapula and the line connecting T7 and the midpoint between T2 and L5 in the sagittal plane; and the angle of internal rotation was measured by the same method as the angle of posterior tilting in the transverse plane.

elevation. Two examiners tried to mark the position of the inferior angle 3 times and calculated interobserver and intraobserver reliability. We then used the most immediate marker to calculate each angle. We also recorded the course and moving distance of the inferior angle over the scapular movement.

Assuming that the scapula lies at 30° to the coronal plane, each subject stood in front of the wall, 30° to the coronal plane. The subjects were given several practice trials to ensure that they understood the proper movement pattern and timing before measurement. They attempted to raise the arm in 6 seconds, maintain maximum elevation for 3 seconds, and then lower the arm in 6 seconds in the scapular plane. Such a speed of movement was chosen because of technical limitation of recording. For measurements, all subjects elevated and lowered the dominant and nondominant arms in the scapular plane 5 times each, according to instructions of the supervisor of the measurements, who randomly told them which arm to elevate. The obtained data were analyzed by use of Kineanalyzer software (Kissei Comtec, Nagano, Japan).

The axis of the humerus was designated as the line connecting the midpoint of the coracoid process and the acromial angle with the midpoint of the lateral and medial epicondyles. The line drawn between the root of the scapular spine and the acromial angle was defined as the line of the scapular spine. The starting angles of both the humerus and the scapular spine were set at 0°. When we recorded the arm-trunk angle, the angles of upward rotation, posterior tilting, and internal rotation of the scapula were simultaneously investigated as scapular 3D motions at each 10° increment during elevation and lowering. Each angle of scapular motion was measured as follows: the angle of upward rotation was calculated from the angle between the scapular spine and the line from T2 to L5; the angle of posterior tilting was calculated from the angle between the line connecting the base of the scapular spine and the inferior angle of the scapula and the line connecting T7 and the midpoint between T2 and L5 in the sagittal plane; and the angle of internal rotation was measured by the same method as the angle of posterior tilting in the transverse plane (Figure 1). In addition, each measured angle was automatically corrected from the numeric value of 3D leaning of the thoracic spine.

We finally compared the angle of scapular upward rotation between subjects whose scapula rotated downward at the initial phase and those whose scapula rotated upward. A similar observation was conducted with respect to the terminal phase of lowering.

Data analysis

Three healthy subjects (all men, aged 22-30 years) participated in the repeatability test via the computerized 3D motion analyzer. We measured both extremities, randomly elevated and lowered 5 times, on 1 day (the first day) and repeated the same measurements 1 week later (the second day). We measured 3D angular displacements for 5 repeated raising and lowering trials for each of the subjects, and the values were used to calculate intraclass correlation coefficients [ICC(1,5)] for 3 types of scapular rotation.

Analysis of variance was performed to compare the 3 rotational motions of the scapula between the dominant and nondominant arms at each 10° increment. To estimate the difference between each arm-trunk angle, we performed the Wilcoxon rank sum test. All statistical testing was performed with SPSS for Windows, version 16.0 J (SPSS Japan, Tokyo, Japan), with the level of significance set at $P < .05$.

Results

Error due to skin slippage of the markers was 1.2 ± 1.0 cm for the base of the scapular spine, 0.7 ± 0.6 cm for the acromial angle, and 0.8 ± 1.0 cm for the coracoid process as measured with radiography, and the markers of the

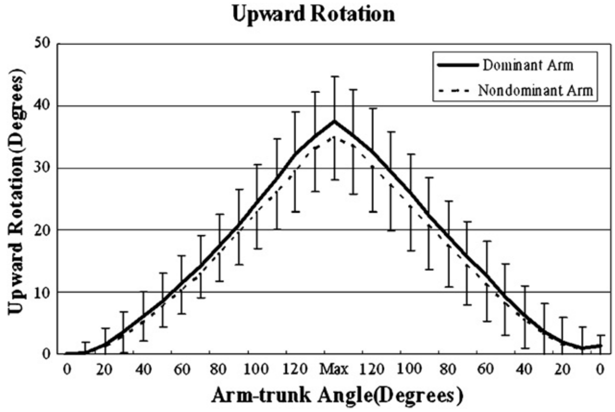

Figure 2 Upward rotation of scapula during arm elevation and lowering. The mean angle of maximum upward rotation was 37.6° ± 7.2° for dominant arms and 44.8° ± 6.8° for nondominant arms. Error bars represent SDs. There was no statistically significant difference between both arms (*P* = .24).

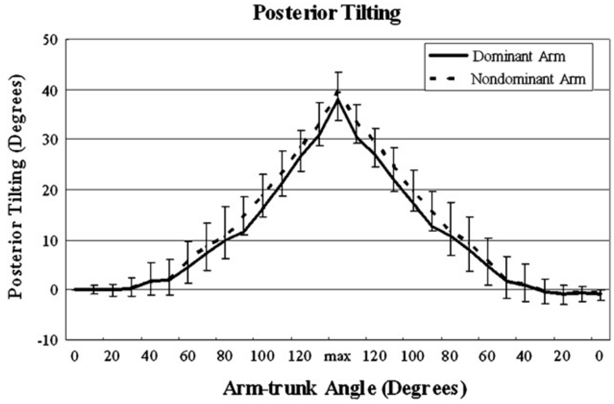

Figure 3 Posterior tilting of scapula during arm elevation and lowering. The mean angle of maximum posterior tilting was 37.9 ± 6.5° for dominant arms and 39.5 ± 5.9° for nondominant arms. Error bars represent SDs. No statistically significant difference was found between both arms (*P* = .07).

medial and lateral epicondyles ranged within 0.5 cm with surface palpation. Overall, the system was found to be accurate within 0.07 mm at rest and 0.42 mm at motion for length, with angular orientations of 0.13° at rest and 0.62° at motion. The repeatability for each scapular motion was high on the first day, second day, and both days: the ICC for upward rotation of the scapula ranged between 0.99 and 1.0; posterior tilting, 0.97 and 0.99; and internal rotation, 0.78 and 0.98.

Two examiners tried to mark the position of the inferior angle 3 times and calculated interobserver and intraobserver reliability. Interobserver reliability [ICC(2,3)] and intraobserver reliability [ICC(1,3)] were 0.93 and 0.97, respectively, at the starting position; 0.92 and 0.94, respectively, at 60°; 0.89 and 0.93, respectively, at 90°; and 0.96 and 0.94, respectively, at maximum elevation.

Regarding the static observation, it was noteworthy that the inferior angle moved almost transversely from the starting position to the position at maximum elevation. The moving distance of the inferior angle was 13.3 ± 2.4 cm transversely and 1.5 ± 1.8 cm horizontally for dominant arms and 12.3 ± 2.4 cm and 1.6 ± 1.8 cm, respectively, for nondominant arms.

The mean humeral and scapular positions at the starting position were 7.5° ± 3.1° for humeral elevation, 0.7° ± 5.4° for scapular upward rotation, 9.6° ± 3.9° for anterior tilting, and 33.1° ± 8.7° for internal rotation. The starting angles of both the humerus and the scapular spine were set at 0°. The mean maximum arm-trunk angles were 135.4° (range, 125.0°-150.0°) for dominant arms and 135.3° (range, 123.3°-153.1°) for nondominant arms. A consistent pattern of scapular upward rotation, posterior tilting, and internal rotation in the scapular plane are shown in Figures 2, 3, and 4. The mean maximum upward rotational angle, internal rotational angle, and posterior tilting angle were 37.6° ± 7.2°, 37.9° ± 6.5°, and 36.8° ± 12.2°, respectively, for dominant arms, and these angles for nondominant arms

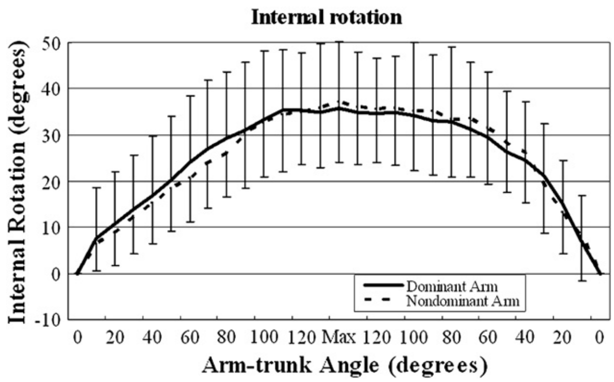

Figure 4 Internal rotation of scapula during arm elevation and lowering. The mean angle of maximum internal rotation was 36.8 ± 12.2° for dominant arms and 37.1 ± 12.0° for nondominant arms. Error bars represent SDs. There was no statistically significant difference between both arms (*P* = .98).

were 44.8° ± 6.8°, 39.5° ± 5.9°, and 37.1° ± 12.0°, respectively. There was no significant difference in the upward rotational angle of the scapular spine (*P* = .24), posterior tilting (*P* = .07), and internal rotation (*P* = .98) between dominant and nondominant arms.

Investigation of scapular motion at the initial phase of elevation and the terminal phases of lowering indicated that the bilateral scapulas rotated downward in 8 subjects and did not rotate downward in 8 subjects, and contradistinctive scapular movement between the dominant and nondominant arms took place in 5 subjects at the initial phase of elevation. At the terminal phase, the bilateral scapulas rotated upward in 9 subjects and did not rotate upward in 4 subjects, and contradistinctive scapular motion took place in 8 subjects. We termed one group in which the scapula rotated downward at the initial phase as the GH type (much GH joint motion and less scapular motion), and another group showing no

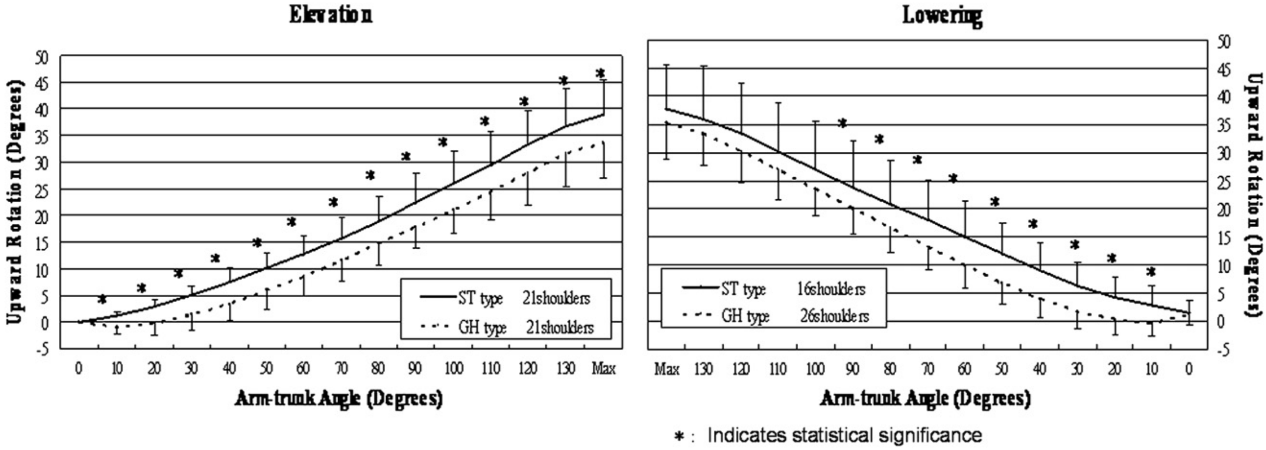

Figure 5 Angle of scapular upward rotation in two types of scapular movement. The first type showed that the scapula rotated downward at the initial phase of elevation and rotated upward at the terminal phase of lowering. This type of movement was termed the glenohumeral (GH) type because there was much GH joint motion and less scapular motion. The second type indicated that the scapula rotated only upward in the initial phase and did not rotate downward at the terminal phase. The second one was termed the scapulothoracic (ST) type because there was much scapular motion and less GH joint motion. The difference in the angles of upward rotation was statistically significant between the GH and ST types. Asterisk (*) indicates significant difference between GH and ST types.

downward rotation in the initial phase was termed as the ST type (much scapular motion and less GH joint motion). In addition, we could classify one group in which the scapula rotated upward at the terminal phase as the GH type and another group in which no scapular upward rotation occurred at the terminal phase as the ST type.

There was a statistically significant difference with regard to the angle of humeral elevation between both types ($P < .02$). Of 21 subjects, 11 elevated and lowered bilateral arms in the same manner. Twenty-one shoulders were classified as the GH type and twenty-one as the ST type during elevation. Interestingly, 6 of 21 shoulders previously classified as the GH type were categorized as the ST type during lowering; in contrast, 11 of 21 previously classified as the ST type were categorized as the GH type (Figure 5). The upward rotational angle of the ST type was greater than that of the GH type; in addition, a statistically significant difference was found in upward rotational angles between both types (Figure 6).

Discussion

We proposed 2 types of upward rotation at the initial phase of elevation: in the GH type (much GH joint motion and less scapular motion), the scapula slightly rotated downward and then progressed upward, and in the ST type (much scapular motion and less GH joint motion), the scapula directly rotated upward. In addition, we could also classify arms as the GH type or ST type at the terminal phase of lowering: in the GH type (much GH joint motion and less scapular motion), the scapula rotated upward at the terminal phase, and in the ST type (much scapular motion and less GH joint motion), the scapula rotated only downward. Our first and second hypotheses were supported. Such scapular movement is interesting and worthy of elucidation. To produce the complex kinematics at the shoulder during arm elevation and lowering, complementary actions of the ST and GH muscles are required. Electromyographic studies have also greatly increased our understanding of relative muscular contributions. The statistically significant difference between the GH type and ST type means that the muscle contribution may be maintained during elevation and lowering.

We observed that the inferior angle moved transversely during humeral elevation; however, this finding has already been proposed by Poppen and Walker[18] and Bagg and Forrest,[1] who showed the transverse motion of the inferior angle in their figures. The movement of the inferior angle on the thorax is assumed to consist of 3 types of scapular rotation. We think that palpating the movement of the inferior angle of the scapula is simple and an easy method to diagnose scapular dyskinesis.

Scapular kinematics has been studied by various methods. Many classical research studies used 2-dimensional analysis of radiographs to document scapular position.[1,8,11,18] However, as described previously, scapular motion consists mainly of 3 rotations: upward/downward rotation, anterior/posterior tilting, and internal/external rotation.[13] Several investigators have reported on direct 3D measurement of scapular kinematics using a magnetic tracking device or magnetic resonance imaging.[2,3,6,7,9,10,13-15,19,22] We summarized mean scapular motion at 120° of elevation in the scapular plane from previous investigations and our study (Table I). Comparisons of our results with previous studies of 3D scapular orientation during humeral elevation are constrained by further complicating factors: differences in

Table I Scapular rotations in literature at 120° in scapular plane

Author	Method	Mean scapular motion (°)		
		Upward rotation	Posterior tilting	Internal rotation
Freedman and Munro[8] (1966)	2D radiographs, standing, static	49	NA	NA
Poppen and Walker[18] (1976)	2D radiographs, standing, static	42	NA	NA
Bagg and Forrest[1] (1988)	2D high speed camera, standing, static	44	NA	NA
Ludewig et al[13] (1996)	3D electromechanical digitizer, sitting, dynamic (elevation 140°)	36	7	20
Lukasiewicz et al[14] (1999)	3D electromagnetic digitizer, standing, dynamic	38	37	43
Graichen et al[10] (2000)	3D MRI, supine position, static	36	16	27
McClure et al[15] (2001)	3D electromagnetic digitizer, standing, dynamic	38	37	43
Dayanidhi et al[6] (2005)	3D electromagnetic digitizer, standing, dynamic	29	7	8
Bourne et al[3] (2007)	3D electromagnetic digitizer, standing, dynamic	49	44	27
Current study	3D motion analyzer, standing, semi-dynamic	31	28	35

2D, Two-dimensional; *NA*, not applicable; *MRI*, magnetic resonance imaging.

instrumentation, planes of analysis, definitions of axis orientations, determination of angular values about the starting position, measuring range, trunk position, and types of subjects, as well as the use of static versus dynamic motion. Given these differences, it is not surprising that variation exists in the literature relating to scapular kinematics. All previous studies reported that the scapula rotated upward, tilted posteriorly, and rotated internally during humeral elevation.[2,3,6,7,9,10,13-15,19,22] The angle of upward rotation in previous studies ranged from 29° to 49° (31° in this study), posterior tilting ranged from 7° to 37° (28° in this study), and internal rotation was between 8° and 43° (35° in this study) (Table I).

The angle of upward rotation has been studied in relation to the SHR.[5,8,11,18] As the scapula rotates downward at the initial phase of elevation in half of 42 shoulders, the angle of upward rotation reduces to under 0° and the SHR is calculated as a large number. The SHR converges to a constant value (SHR, 3.5) according to certain motion of the scapula over 60° of humeral elevation (data not shown). We agree with the statement in which Inman et al[11] identified the setting phase.[23] McClure et al[15] have reported that scapular upward rotation during humeral elevation is best represented by a third-order polynomial curve fit and downward rotation during lowering is represented well by a linear fit. Our results are not completely consistent with previous findings, which could be because of different methods or instrumentation. Posterior tilting of the scapula gradually progresses over 60° to maximum elevation and shows similar regression toward 60° of lowering in this study. Previous researchers showed a similar movement of the scapula with respect to posterior tilting.[3,6,19] Two patterns of angular progression about internal rotation have been investigated: internal rotation occurred approximately linearly throughout humeral elevation[9,10,15,19]; in contrast, the angle progressed like a parabolic curve in our study.[3,6,7] It is difficult to evaluate which pattern represents

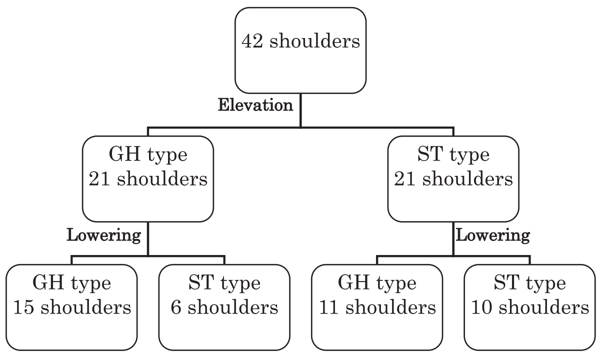

Figure 6 Each number of the glenohumeral and scapulothoracic types during elevation and lowering. Twenty-one of 42 shoulders were classified into the glenohumeral (GH) type and 21 were classified as scapulothoracic (ST) type during arm elevation. In addition, during lowering, 6 of 21 shoulders in the GH type were identified as the ST type, and 11 of 21 in the ST type were verified as the GH type.

the actual movement of internal rotation because of the many factors described previously. If novel 3D instrumentation were available to measure dynamic scapular motion under the condition of standing, accurate 3D motion of the scapula would be visualized and each rotational angle calculated.

These results hold clinical implications: first, we identified 2 types of scapular orientation; second, transverse movement of the inferior angle of the scapula was shown to occur according to our analysis of individual subjects; and lastly, scapular motion consists of 3 rotational movements. When clinicians examine shoulder disorders, they can compare with bilateral shoulders using a current outcome. The posterior tilt motion is believed to be functionally important to allow unhindered motion of the humeral head and the rotator cuff tendons under the anterior aspect of the acromion during humeral elevation.[14,17] The upward rotation difference is a substitution pattern used to accomplish functional elevation.[20] Such abnormal scapular motion, which is a potential source of mechanical dysfunction leading to shoulder disorders, can be frequently detected. Clinicians should carefully observe and improve abnormal scapular movement.[12]

The measurement method had some limitations. Although we used skin markers in static positions and performed dynamic measurements, repeatability was high. In addition, accuracy between the precise location of bony landmarks and the position of skin markers was not completely correct. Our study sample consisted of normal young subjects. Therefore, caution must be used in extrapolating these findings to other populations. Participants in this study did not elevate and lower their extremities with speed, nor did they flex their elbow joints similarly to conditions of motion in daily life, where the speed of motion is generally faster and the arm is elevated with a flexed elbow joint.

Conclusions

Scapular motion consists of 3 rotations. There was no significant difference in the upward rotation, posterior tilting, and internal rotation between dominant and nondominant arms. We found 2 types of scapular upward rotation in the initial phase of elevation and terminal phase of lowering.

Disclaimer

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