Original Article

A comparison of 3D scapular kinematics between dominant and nondominant shoulders during multiplanar arm motion

Sang Ki Lee, Dae Suk Yang, Ha Yong Kim, Won Sik Choy

Abstract

Background: Generally, the scapular motions of pathologic and contralateral normal shoulders are compared to characterize shoulder disorders. However, the symmetry of scapular motion of normal shoulders remains undetermined. Therefore, the aim of this study was to compare 3dimensinal (3D) scapular motion between dominant and nondominant shoulders during three different planes of arm motion by using an optical tracking system.

Materials and Methods: Twenty healthy subjects completed five repetitions of elevation and lowering in sagittal plane flexion, scapular plane abduction, and coronal plane abduction. The 3D scapular motion was measured using an optical tracking system, after minimizing reflective marker skin slippage using ultrasonography. The dynamic 3D motion of the scapula of dominant and nondominant shoulders, and the scapulohumeral rhythm (SHR) were analyzed at each 10° increment during the three planes of arm motion.

Results: There was no significant difference in upward rotation or internal rotation ($P > 0.05$) of the scapula between dominant and nondominant shoulders during the three planes of arm motion. However, there was a significant difference in posterior tilting ($P = 0.018$) during coronal plane abduction. The SHR was a large positive or negative number in the initial phase of sagittal plane flexion and scapular plane abduction. However, the SHR was a small positive or negative number in the initial phase of coronal plane abduction.

Conclusions: Only posterior tilting of the scapula during coronal plane abduction was asymmetrical in our healthy subjects, and depending on the plane of arm motion, the pattern of the SHR differed as well. These differences should be considered in the clinical assessment of shoulder pathology.

Key words: 3D scapular motions, dominance, optical tracking system, scapulohumeral rhythm, shoulder

Introduction

The shoulder complex system consists of three bones (the clavicle, humerus, and scapula) and four joints (sternoclavicular, acromioclavicular, glenohumeral, and scapulothoracic), and shoulder motion consists of a combination of the motion of these four joints.[1,2] Among these, the scapula commonly is seen as an important stable base for glenohumeral function. Scapular motion through a substantial arc is required to maintain optimal muscle length–tension relationships and glenohumeral joint alignment during arm elevation.[3] Thus, scapular motion can play a key role in shoulder dysfunction.[4-9] Changes in the scapular rest position and motion have been observed in subjects with frozen shoulder,[10] impingement syndrome,[5,6,9,11] rotator cuff tears,[8] and shoulder instability,[7] and in those who have undergone shoulder joint replacement.[12] Therefore, detailed studies that define normal parameters in a healthy shoulder complex are required to accurately characterize shoulder abnormalities and to examine diverse therapeutic approaches in order to improve the response to treatment.

Recently, shoulder motion has been estimated dynamically during active elevation in three dimensional (3D) assessments with Roentgen stereophotogrammetry,[13,14] the 3D registration technique,[15] noninvasive electromagnetic tracking devices[16,17] or optical tracking systems,[18,19] and

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pins fixed to the bones,[3,4,20,21] each of these methods has its own advantages and disadvantages. Among these various methods for studying scapular motion, the method in which pins are fixed into the scapulas of living subjects is known to be the most accurate.[3,4,20,21] However, such an invasive method inevitably cause injuries to the normal bones of healthy volunteers. The unnecessary procedure may also limit the extreme and natural motions of the shoulder by preventing skin motion over the bone, which can cause pain. On the other hand, optical tracking systems and electromagnetic tracking devices are noninvasive methods that use skin markers and do not cause pain. However, these devices are not widely used for shoulder 3-D motion analysis because of reflective marker skin slippage. In other words, if reflective marker skin slippage is minimized, these systems could become good alternative methods for shoulder motion analysis.

Generally, to characterize shoulder disorders, scapular motions of pathologic and contralateral normal shoulders are compared, regardless of arm dominance. For example, a test to clinically measure static scapular positions, called the lateral scapular slide test, is used to identify scapular asymmetry, based on the assumption that the movement of the scapula is symmetric.[22,23] However, the symmetry of scapular motion of normal shoulders during different planes of arm motion remains undetermined, despite common practices comparing the kinematics of pathologic and contralateral shoulders using various methods.[22,24-26]

The relationship and contribution between the scapula and the humerus was termed the scapulohumeral rhythm (SHR) by Codman.[27] The SHR is defined as the ratio of glenohumeral to scapulothoracic motion, and has been a simple and reasonable reflection of dynamic motion of the shoulder complex. Previous reports on normal SHR have ranged from 1.35:1 to 7.9:1.[1,3,17,28-31] In recent studies on 3D scapular motion analysis, the SHR mostly was investigated during sagittal plane flexion or scapular plane abduction;[3,17,19] however, studies on SHR during coronal plane abduction are rare.[32]

The aim of this study was to compare the 3-D scapular motion and the SHR between dominant and nondominant shoulders during three different planes of arm motion, and identify any scapular bony landmarks that could minimize reflective marker skin slippage when using an optical tracking system. We hypothesized that there would be no differences in scapular motion between the dominant and nondominant shoulders during the three planes of arm motion.

Materials and Methods

Twenty six healthy subjects (all men) participated in this study, which was approved by our institutional review board. Subjects were excluded if they had any medical history or pain in any shoulder; any restriction of range of motion (ROM), compared with the contralateral shoulder or established norms; reproduction of shoulder pain on any clinical examination; visible scapular dyskinesia during repeated elevation and lowering of the arm; scoliosis or asymmetry of the thoracic cage; or body mass index (BMI) over 25 kg/m^2 as obese subjects may show an increase in reflective marker skin slippage. Among the 26 subjects, 2 were excluded because of restricted ROM and 4 were excluded because of asymmetry of the thoracic cage; therefore, 20 subjects were included in this study. The average age, height, weight, and BMI of the 20 subjects were 29.1 years (range, 27-34 years), 1.75 m (range, 1.65-1.85 m), 69.5 kg (range, 59.3-80.4 kg), and 22.5 kg/m^2 (range, 20.7–24.5 kg/m^2), respectively. All subjects were right-hand dominant.

The 3-D scapular motion was estimated using an optical tracking system (Motion Analysis Corporation, Santa Rosa, CA, USA), which required at least three noncollinear markers on each bone. This system was composed of six synchronized infrared cameras placed circumferentially around the subject being examined, allowing for 120-Hz data capture [Figure 1].

Before performing this study, we used ultrasonography to identify the locations where reflective marker skin slippage was minimal in all subjects. A 12-MHz linear array transducer of the Philips iU22 scanner (Philips Medical Systems, Andover, MA, USA) was used. Skin slippage was

Figure 1: A clinical photograph showing a subject with attached reflective markers being examined using an optical tracking system, which is composed of six synchronized infrared cameras, allowing for 120-Hz data capture

measured on the scapula where palpation is possible, such as the coracoid process, the most anterosuperior aspect of the acromioclavicular joint, midpoint between the most anterosuperior aspect of the acromioclavicular joint and the angle of acromion, the angle of acromion, the base of the scapular spine, and the inferior angle of the scapula. Skin slippage was defined as the distance between the point that was marked on the skin by a pen after identifying the accurate bony landmark using ultrasonic waves in the resting position and the point of the accurate bony landmark identified using ultrasonic waves at 30°, 60°, 90°, and maximum sagittal plane elevation. Mean skin slippage is summarized in Table 1. According to these results, the scapular segment was created using the following three points: midpoint between the most anterosuperior aspect of the acromioclavicular joint and the angle of acromion, the angle of acromion, and the base of the scapular spine. The disadvantage of using the bony landmarks of the scapula in this study was that the tilting value of the scapular spine was measured rather than that of the scapular body in the resting position. We also attached a reflective marker on the inferior angle of the scapula. To obtain the static position of the scapula, we used the angle of acromion, the base of the scapular spine, and the inferior angle of the scapula at the static position alone. Humeral and thoracic marker positions were chosen from those recommended by the International Society of Biomechanics: the seventh cervical vertebra, the eighth thoracic vertebra, the jugular notch and the xiphoid process of the sternum, the lateral epicondyle, and the medial epicondyle.[33] The glenohumeral rotation center was estimated from the scapular bony landmarks using regression analysis.[34] With the subject's chest wall and both arms exposed, 0.9-cm reflective markers (Motion Analysis Corporation, Santa Rosa, CA) were attached on the bony landmarks of the trunk, scapula, and humerus [Figure 1].

Motion testing was performed in a standardized sitting position with the trunk in an erect position, the knees and hips flexed at 90°, and the feet flat on the floor. Lines were drawn on the laboratory floor according to each plane of arm motion [Figure 2a]. We asked the subjects to direct their thumbs parallel to each line in order to minimize the rotation of the humerus and guide the appropriate arm motion. To determine whether the arm motion was appropriate, we confirmed whether the reflective marker on the thumbnail was coincident with the line on the laboratory floor using Eva Real Time (EVaRT) 5.0 and Skeletal Builder (SkB) software (Motion Analysis Corporation) [Figure 2b]. Before measurements were obtained, the subjects were given several practice trials to ensure that they understood the proper movement pattern and timing. We asked the subjects to move both arms simultaneously and to complete five repetitions of each motion.

Table 1: Results of the mean skin slippage of scapular bony landmark using ultrasonography in the 30°, 60°, 90°, and maximal sagittal plane elevation

Scapular bony landmark	Skin slippage (cm)
Coracoid process	1.5±1.2
AC joint	1.7±1.5
Midpoint of the AC joint and the AA	0.8±0.5
AA	0.5±0.6
Base of the scapular spine	1.1±0.9
Inferior angle of scapula	2.3±1.7

AC = Acromioclavicular, AA = Angle of acromion

The data represents the active and dynamic scapular motions during sagittal plane flexion, scapular plane abduction, and coronal plane abduction. Sagittal plane flexion was defined as arm movement from the body parallel to the sagittal plane of the trunk (90° anterior to the coronal plane). Scapular plane abduction was performed at 40° anterior to the coronal plane. Coronal plane abduction was defined as arm movement from the body parallel to the coronal plane of the trunk (0° anterior to the coronal plane). The subjects were instructed to both elevate and lower the arm for approximately 3 s for each motion, for a total of 6 s for the full available ROM. The obtained data were analyzed using EVaRT 5.0 and SkB software. EVaRT is a basic program that captures and edits data obtained from six synchronized infrared cameras. SkB is a program that creates each bony segment by using combinations of reflective markers and calculates 3-D movements of bony segments, edited by EVaRT, in order to allow transformation of the data from a global coordinate system to an anatomically based local coordinate system.

In this study, the orientations of the scapula and the humerus relative to the trunk were taken into account. The starting angles of both the humerus and the scapula were set at 0°. (When we recorded the arm–trunk angle; the angles of upward rotation, internal rotation, and posterior tilting of the scapula were obtained simultaneously as 3-D scapular motions at each 10° increment during elevation and lowering of the arm). After the scapula's anatomical landmarks were computed, a local coordinate system of the scapula was created, as recommended by the ISB.[33] Scapular orientation with respect to the trunk was described

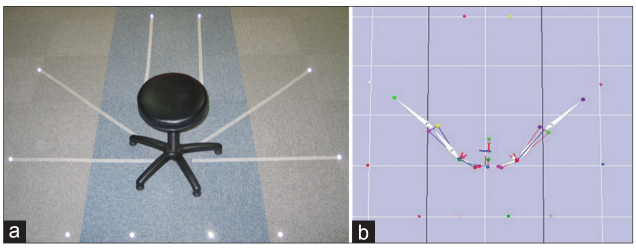

Figure 2: (a) To identify the proper arm motion, lines were drawn with attached reflective markers. (b) Software was used to confirm whether the arm motion was appropriate with reflective markers attached to the thumb and floor

using the YXZ′ Euler sequence. Internal/external rotation was around the vertical axis of the trunk, followed by upward/downward rotation around the perpendicular axis of the scapula plane pointing forward, followed by anterior/posterior tilt around the horizontal axis of the scapular spine.

In addition, five healthy subjects (all men; age range, 27-34 years) participated in a repeatability test using our optical tracking system. We obtained measurements for both shoulders, randomly elevated and lowered five times on the first day and repeated the same measurements 1 week later. We estimated 3D angular motion for five repeated elevation and lowering trials for each of the subjects, and the values were used to calculate intraclass correlation coefficients [ICCs (1,5)] and the standard error of measurement for three types of scapular rotation.

After determining trial-to-trial repeatability, the mean values and SDs of the angles of the arm and scapula were obtained. The variance was analyzed to compare the three rotational motions of the scapula and the SHR between dominant and nondominant shoulders at each 10° increment during the three planes of arm motion. SHR was defined as the ratio of the increment in glenohumeral elevation (ΔG) relative to the increment in scapular upward rotation (ΔS). The increment in humeral elevation (ΔH) was the sum of ΔG and ΔS. Therefore, the SHR was calculated as $(\Delta H - \Delta S)/\Delta S$. Overall SHR between the arm in the resting position and at maximum elevation positions was calculated using this formula. To estimate the SHR at each 10° increment of humeral elevation, we performed the calculation in two steps. First, $\Delta S/\Delta H$ was computed as the slope of the polynomial regression line, using scapular upward rotation as the independent value and the humeral elevation angle as the dependent value. Then, the SHR was calculated as $1/(\Delta S/\Delta H) - 1$.[15]

The Wilcoxon rank-sum test was used to estimate the difference between each arm–trunk angle. All statistical analyses were performed using SPSS version 18.0 software (IBM Corporation, Armonk, NY, USA), with the level of significance set at $P < 0.05$.

Results

The overall accuracy of our system was within 0.03 mm at rest and 0.27 mm at motion for length, and within 0.09° at rest and 0.43° at motion for angular orientations.

The repeatability of each scapular motion was high on the first day, second day, and both days: the ICC for upward rotation of the scapula ranged between 0.95 and 0.98; internal rotation, 0.96 and 0.99; and posterior tilting, 0.9 and 0.95. The standard error of measurement values across the five trials averaged 1.5°, 1.7°, and 1.8° for sagittal plane flexion, scapular plane abduction, and coronal plane abduction, respectively.

The mean humeral and scapular positions at the starting position are provided in Table 2. The starting angles of both the humerus and scapula were set at 0°. The mean maximum arm–trunk angles were 143.1° (range, 132.0°-157.0°) for dominant shoulders and 143.0° (range, 136°-160°) for nondominant shoulders.

The mean upward rotation, internal rotation, and posterior tilting of the scapula of the dominant and nondominant shoulders during sagittal plane flexion, scapular plane abduction, and coronal plane abduction are provided in Figures 3a-c, 4a-c, and 5a-c. There was no significant difference in upward rotation or internal rotation of the scapula between both shoulders during the three planes of arm motion. However, there was a significant difference in posterior tilting of the scapula ($P = 0.018$) during coronal plane abduction [Table 3].

The average overall SHRs during the three planes of arm motion are shown in Figure 6a-c and Table 4. There was no significant difference in SHR between both shoulders [Table 4]. However, the pattern of SHR was different depending on the plane of arm motion. During sagittal plane flexion and scapular plane abduction, the SHR was a

Table 2: Humeral and scapular positions at the starting point

	Dominant (degrees)	Nondominant (degrees)
Humerus		
Elevation	7.4±3.5	6.5±3.1
Scapula		
Upward rotation	10.5±6.6	11.5±12.2
Internal rotation	30.6±6.3	30.1±6.3
Posterior tilting	−10.5±4.6	−12.1±10.3

Table 3: Mean angles during three different planes of arm motion

	Dominant (degrees)	Nondominant (degrees)	*P* value
Sagittal plane flexion			
Upward rotation	49.7±5.7	51.9±7.1	0.663
Internal rotation	38.4±4.5	40.9±7.0	0.504
Posterior tilting	22.1±4.8	20.1±4.7	0.231
Scapular plane abduction			
Upward rotation	53.8±4.8	55.3±9.5	0.926
Internal rotation	43.1±3.4	45.7±8.7	0.816
Posterior tilting	25.0±4.7	23.7±4.8	0.171
Coronal plane abduction			
Upward rotation	51.5±5.2	53.2±9.5	0.446
Internal rotation	42.4±4.5	44.6±8.8	0.312
Posterior tilting	21.0±4.3	17.8±4.6	0.018

large positive or large negative number in the initial phase of elevation and in the last phase of lowering, and was maintained consistently afterward. However, the pattern of SHR was different during coronal plane abduction [Figure 6a-c].

Discussion

This study demonstrated that 3D scapular motion and the SHR were symmetrical between dominant and nondominant shoulders, except posterior tilting during coronal plane abduction, and that the SHR pattern during coronal plane abduction was different from those during sagittal plane flexion and scapular plane abduction.

Table 4: The average scapulohumeral rhythm

	Dominant	Nondominant	*P* value
Sagittal plane flexion	2.0:1	1.8:1	0.095
Scapular plane abduction	1.8:1	1.7:1	0.471
Coronal plane abduction	1.9:1	1.8:1	0.731

Among the various methods used for studying scapular motion, the method involving pin fixation into the scapulas of living subjects is known to be the most accurate.[3,4,20,21] However, such an invasive method has complications and disadvantages. Therefore, we used a noninvasive optical tracking system (and minimized reflective marker skin slippage). To confirm the locations of reflective markers, methods involving palpation[35-37] and radiography[18-20] are widely used. However, ultrasonography was used in the present study to identify accurate bony landmarks; this

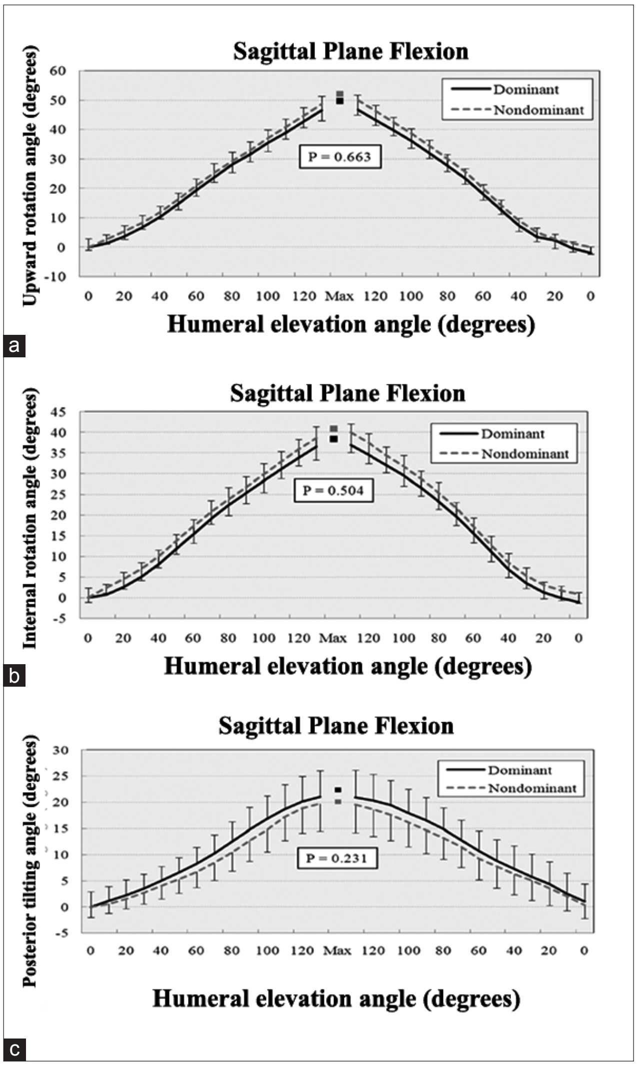

Figure 3: These graphs show the measured angle of scapular motion between dominant and nondominant shoulders during sagittal plane flexion. There was no significant difference in upward rotation (a) internal rotation (b) or posterior tilting (c) of scapular motion between both shoulders

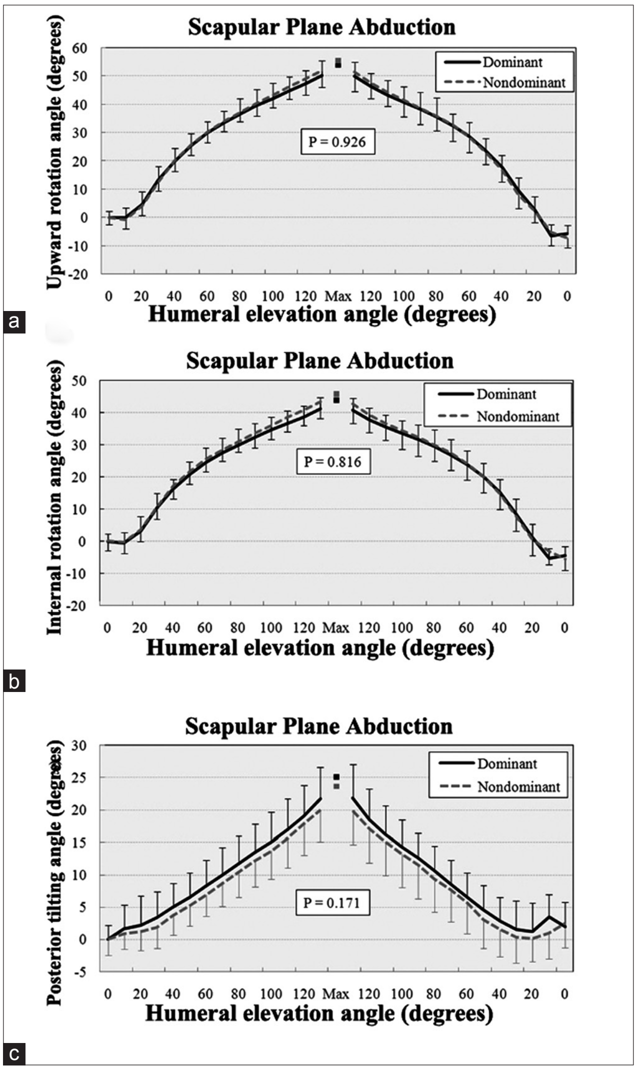

Figure 4: These graphs show the measured angle of scapular motion between dominant and nondominant shoulders during scapular plane abduction. There was no significant difference in upward rotation (a) internal rotation (b) or posterior tilting (c) of scapular motion between both shoulders

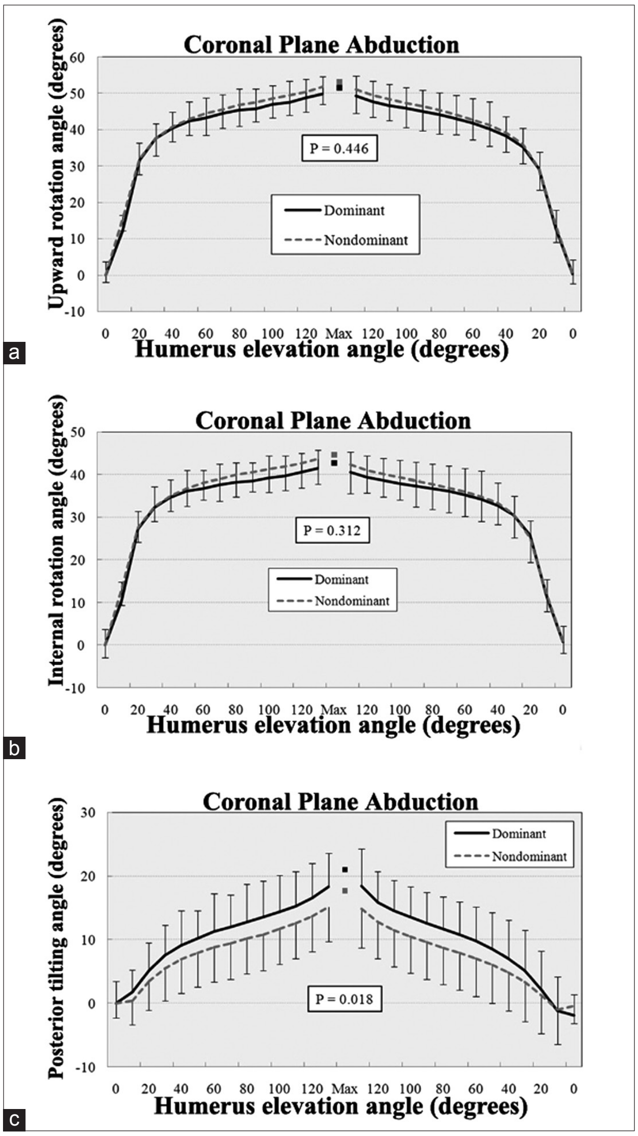

Figure 5: These graphs show the measured angle of scapular motion between dominant and nondominant shoulders during coronal plane abduction. There was no significant difference in upward rotation (a) or internal rotation (b) of scapular motion between both shoulders. However, posterior tilting (c) of scapular motion was significantly different between both shoulders

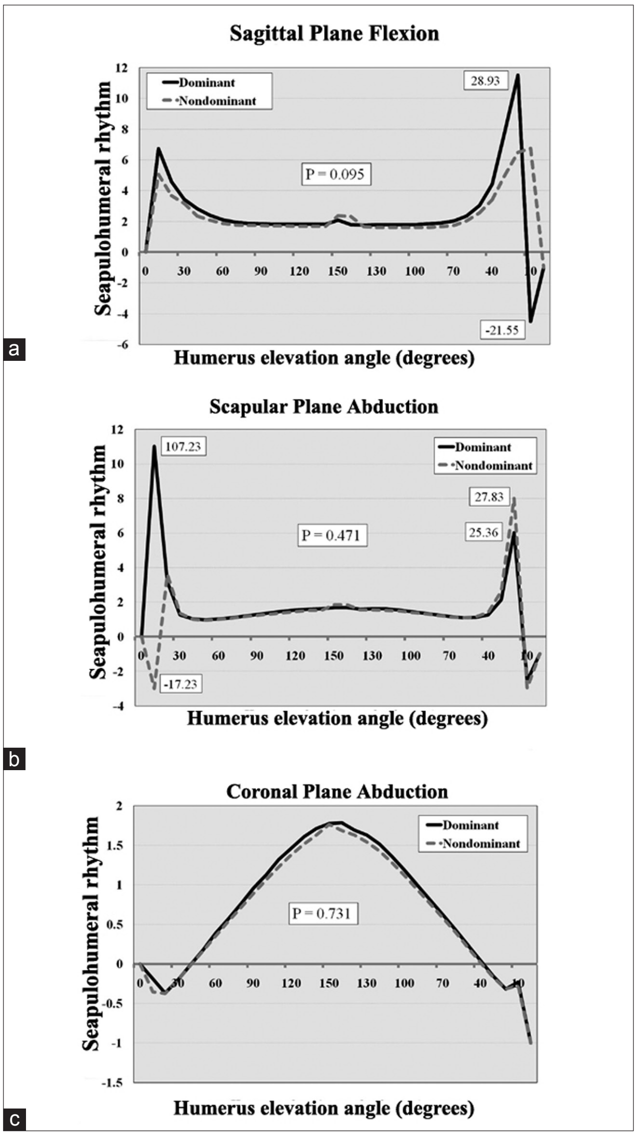

Figure 6: These graphs show the scapulohumeral rhythm (SHR) of both shoulders during sagittal plane flexion (a) scapular plane abduction (b) and coronal plane abduction (c) There was no significant difference in the SHR during sagittal plane flexion, scapular plane abduction, or coronal plane abduction between both shoulders. However, in the early phase of arm elevation during coronal plane abduction, the SHR showed greater upward rotation of the scapula than glenohumeral motion, which was different than that observed during sagittal plane abduction and scapular plane abduction

modality enables more accurate selection of position than palpation does. Moreover, since radiation exposure by ultrasonography is much less than that of radiography, this method is considered to be an alternative to identify accurate locations for reflective markers.

Several previous studies reported 3D motion of the scapula using various techniques, and bone-fixed tracking markers are thought to be the current gold standard for precise measurement of shoulder motion.[38] The angular values of scapular motion during scapular plane elevation, analyzed with bone-fixed tracking, were reported to be 40°–50°, 20°–30°, and 2°–24° in upward rotation, posterior tilt, and external rotation, respectively.[3,20] However, most previous studies reported that the scapula rotated upward, tilted posteriorly, and rotated internally during humeral elevation.[6,10,18,19,21,39-43] The angular values of scapular motion analyzed in this study were 49°–55°, 38°–45°, and 17°–25° in upward rotation, external rotation, and posterior tilt, respectively, depending on the different planes of humeral elevation. The reasons for these discrepancies in measurements of scapular motion include differences in instrumentation, planes of analysis, definition of axis orientation, determination of angular value around the starting position, measuring range, trunk position, types of subjects, and the use of static versus dynamic motion. Due to these discrepancies, diverse scapular motions are reported in studies, and simple comparison is not appropriate.

The symmetry of scapular position and motion between dominant and nondominant shoulders remains in debate.[9,15,18,19,44,45] In the present study, only posterior tilting during coronal plane abduction was significantly different between both shoulders ($P = 0.018$). The trapezius, serratus anterior, and pectoralis minor muscles play an important role in producing posterior tilting of the scapula.[36,46,47] Among them, the pectoralis minor muscle is the only anterior scapulothoracic muscle, and is passively lengthened during active scapular upward rotation, external rotation, and posterior tilting, which occurs during arm elevation in healthy individuals.[3,5] However, if the pectoralis minor muscles become adaptively shortened, they may demonstrate greater passive tension when elongated, resulting in earlier engagement of the passive elements at shorter muscle lengths, and also in higher passive tension as the origin and insertion of this muscle are separated during arm elevation, especially during coronal plane abduction.[48] According to the present study, since the nondominant shoulder is more anteriorly tilted than the dominant shoulder in the static position, the pectoralis minor is shortened in the nondominant shoulder compared with the dominant shoulder. Therefore, we believe that posterior tilting of the scapula produced larger movement in the dominant shoulder than in the nondominant shoulder, and posterior tilting of the scapula showed significant asymmetry in both shoulders, especially during coronal plane abduction.

It is generally accepted that larger glenohumeral motion occurs as opposed to upward rotation of the scapula during the early phases of arm elevation.[3,17,19,32] In the present study, although sagittal plane flexion and scapular plane abduction showed similar SHR pattern as those in other studies, there was a different SHR pattern during coronal plane abduction. In the early phase of coronal plane abduction, upward rotation of the scapula is larger than glenohumeral motion. The reason for a different SHR pattern during coronal plane abduction is that the upper trapezius and serratus anterior muscles act at a much higher magnitude in upward rotation of the scapula during early coronal plane abduction than during sagittal plane flexion or scapular plane abduction. Therefore, we believe that upward rotation of the scapula occurred to a greater extent than glenohumeral motion during early coronal plane abduction.

The measurement method used in the present study has some limitations. Although reflective marker skin slippage was not completely eliminated, repeatability was high. In addition, we tried to minimize skin slippage by excluding subjects with a BMI of ≥ 25 kg/m^2. In addition, with the use of ultrasonic waves, which are not radioactive and are noninvasive, we tried to minimize the error between the locations of bony landmarks and skin markers. Another limitation is that the subjects in this study were all males in a narrow age range. Since scapular motions are affected by sex and physical build, additional studies with various population groups are necessary in the future.

To conclude although it may be difficult for clinicians to detect shoulder abnormalities in clinical settings, comparison of scapular motions in dominant and nondominant shoulders for characterizing shoulder abnormalities, or for examining diverse therapeutic approaches for improving the response to treatments, should be thoughtfully conducted because scapular motions are asymmetric, and can be different depending on the plane of humeral elevation.

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