Analysis of scapular kinematics in three planes of shoulder elevation: A comparison between men and women

Hiroko Nakayama^{1,2*}, Hideaki Onishi^{2,3}, Motoko Nojima¹, Katsuhito Ishizu¹ and Masayoshi Kubo^{2,3}

¹ Department of Rehabilitation, Niigata Central Hospital, 1-18 Shinko-cho, Chuo-ku, Niigata 950-8556, Japan

² Graduate School, Niigata University of Health and Welfare, 1398 Shimami-cho, Kita-ku, Niigata 950-3102, Japan

³ Department of Physical Therapy, Niigata University of Health and Welfare, 1398 Shimami-cho, Kita-ku, Niigata 950-3102, Japan

Received: July 15, 2017 / Accepted: December 1, 2017

Abstract The aim of this study was to compare scapular kinematics between men and women during shoulder flexion, scapular plane elevation, and shoulder abduction. Eleven healthy men and 11 healthy women participated in this study. As participants performed shoulder flexion, scapular plane elevation, and abduction at a consistent speed, an electromagnetic motion capture system was used to analyze scapular motion. The change in scapular orientation from its resting position was calculated at 30°, 60°, 90° and 120° of humeral elevation. The study found that scapular upward rotation and posterior tilt angles increased significantly with each successive humeral elevation angle, but less so in women than in men. Scapular internal or external rotation differed significantly according to the plane of elevation, that is the scapula was internally rotated during flexion, with no change during scapular plane elevation, and it was externally rotated during abduction. This variation was more marked in women. This study revealed gender differences in scapular kinematics during shoulder motion. During shoulder elevation, the scapulothoracic joint played a greater role in men than in women, whereas the glenohumeral joint played a greater role in women.

Keywords : scapular motion, gender difference, kinematics, shoulder elevation

Introduction

The shoulder complex consists of the glenohumeral, acromioclavicular, sternoclavicular, and scapulothoracic joints with twenty surrounding muscles, allowing for complex types of motion¹. The scapula alone can move in various ways. Many studies have measured and analyzed shoulder motion with a variety of methods²⁻⁸. Scapulohumeral rhythm changes with load or velocity and with the phase of the elevation angle, and thus its value is not constant⁸⁻¹⁰. It is commonly thought that the collapse of scapulohumeral rhythm may predict glenohumeral dysfunction^{3,5,11}. Upward rotation, posterior tilt, and internal rotation of the scapula reportedly increase with glenohumeral elevation, and the internal and external rotation angles differ significantly between the planes of elevation during glenohumeral flexion, scapular plane elevation, and abduction⁴. Many previous studies of scapular kinematics have considered various planes of elevation and tasks. However, it has often been assumed when comparing asymptomatic and symptomatic subjects that there is no gender difference^{6,12,13}. Recent reports, though, suggest that gender may influence scapular kinematics¹⁴, and there have been a few studies exploring gender differences¹⁴⁻¹⁶.

One reported effect of gender is that women have a significantly greater range of motion than men¹⁷. Studies indicating a gender difference in scapular kinematics^{15,16} have demonstrated that external rotation of the scapula was significantly greater in women than in men for flexion and abduction at 120°, with the mean differences being 13° for flexion and 7° for abduction. However, these authors investigated only two planes of elevation, i.e., flexion and abduction, and did not assess scapular plane elevation. Furthermore, their participants performed the movements at self-chosen, and thus inconsistent speeds.

In the resting position, the scapula sits on the thorax at a 30° to 40° angle anterior to the coronal plane¹⁸. The scapular plane elevation is to elevate the humerus with reference to this angle of the scapula. A scapular plane elevation of 130° to 150° is said to be zero-position, because muscular rotatory forces acting on the humerus at this position are almost zero; and the zero-position is reported to be important for management after rotator cuff injury¹⁹. Understanding scapular kinematics during scapular plane elevation is important for clinicians, since the kinematic data helps determine appropriate physical therapy after shoulder injury or surgery.

The aim of this study was to investigate the effect of gender and the plane of elevation on scapular kinematics during glenohumeral flexion and abduction, including

*Correspondence: hnakayama826@gmail.com

scapular plane elevation, performed at a constant speed.

Materials and Methods

Participants. Eleven healthy men (age, 26.1 ± 2.9 years [mean $\pm$ SD]; height, 171.9 ± 5.5 cm; weight, 62.6 ± 6.9 kg) and 11 healthy women (age, 27.8 ± 6.2 years; height, 156.5 ± 4.4 cm; weight, 50.9 ± 5.1 kg) participated in this study. The participants had no previous history of shoulder injury and no neuromuscular disease. In each case, the right shoulders was examined. The study procedures were explained to each participant, and their consent was obtained; and the informed consent process and procedures were approved by Niigata University of Health and Welfare Institutional Review Board (Approval Number 17005-060215).

Instrumentation. Three-dimensional kinematic data of the scapula and humerus were recorded with an electromagnetic motion tracker system (Liberty; Polhemus Inc., Colchester, VT, USA). The transmitter was fixed on an 80 cm high wooden table set 20 cm behind the right upper arm of the participant. We used three sensors for analysis. With participants sitting with their arms relaxed at their sides, the first and second sensors were fixed to the skin on the superior border of the sternum and the superior acromion process using double-sided tape, and the third was fixed on the back of the distal humerus with the original thermoplastic cuff and Velcro® straps (Fig. 1).

A global coordinate system was established in the transmitter, and this provided the basis for the data from the sensors. Following the recommendations of the International Society of Biomechanics (ISB) guidelines²⁰ the bony landmarks of the thorax, scapula, and humerus,

were recorded using another Liberty sensor to establish the local coordinate systems (LCS) of each segment. The spinous process of the seventh cervical vertebra (C7), the suprasternal notch (SN), the spinous process of the eighth thoracic axis (T8), and the xiphoid process (XP) were used to define the LCS of the thorax (LCS-t). The origin was coincident with the SN. The Yt-axis was the line from the midpoint between the XP and T8 to the midpoint between the SN and C7. The Zt-axis was the line perpendicular to the plane formed by the SN, C7, and the midpoint between the XP and T8, pointing to the right. The Xt-axis was the line perpendicular to the Zt- and Yt-axes, pointing forward (Fig 2A). The trigonum spinae (TS), inferior angle of the scapula (IA), and acromial angle (AA) were used to define the LCS of the scapula (LCS-s). The origin was coincident with the AA. The Zs-axis was the line from the TS to the AA. The Xs-axis was the line perpendicular to the plane formed by the AI, AA, and TS, pointing forward. The Ys-axis was the common line perpendicular to the Xs- and Zs-axes pointing upward (Fig. 2B). The medial epicondyle (ME), lateral epicondyle (LE), and center of the glenohumeral joint (GH) were used to define the LCS of the humerus (LCS-h). The origin was coincident with the GH. The Yh-axis was the line from the midpoint of the LE and ME to the GH. The Xh-axis was the line perpendicular to the plane formed by the LE, ME, and GH, pointing forward. The Zh-axis was the common line perpendicular to the Yh- and Xh-axes, pointing to the right (Fig. 2C).

Procedures. Each participant performed humeral elevation and lowering in a range of 0° to 130° in three planes: glenohumeral flexion, scapular plane elevation relative to a plane orientated 40° anterior to the coronal plane, and abduction.

Fig. 1 Position of each sensor.

(A): Sternum sensor: Fixed to the skin on the superior border of the sternum using double-sided tape.

(B): Scapula sensor: Fixed to the skin on the superior acromion process using double-sided tape. Humerus sensor: Fixed on the back of the distal humerus with the original thermoplastic cuff and hook-and-loop fastener.

(C): Subject performed scapular plane elevation at 120° degrees.

Fig. 2 Locations of the anatomical landmarks used for the digitization and establishment of coordinate axes for each segment. The illustrations show the landmarks and local coordinate axes used for the thorax, scapula, and humerus segments, respectively.

Fig. 3 Definitions for scapular motion. Scapula rotations were defined in accordance with the recommendations of the International Shoulder Group. (A): Upward/downward rotation seen in a posterior view of the right shoulder. (B): Anterior/posterior tilt seen in a lateral view of the right shoulder. (C): Internal/external rotation seen in a posterior view of the right shoulder.

Participants sat on a chair with a low backrest with the trunk in a neutral position and both feet on the ground; they kept the elbow extended and the forearm in a neutral position. Five repetitions of elevation and lowering were completed at a rate of one cycle in 6 seconds (s), using a metronome to control the speed. Elevation and lowering were randomly performed in three planes, with resting for two minutes between each elevation task. Prior to elevation, data were recorded with the arm at the side to define the resting position. The tasks were explained to each participant beforehand and they were asked to practice maintaining an elevation of 130°, using a mirror on which was marked the appropriate position of their fingertips.

Data reduction. Position and orientation data for the thorax, scapula, and humerus from each sensor were collected at a sampling rate of 120 Hz. The scapular rotation angle relative to thorax was defined as follows: in accordance with International Shoulder Group (ISG) recommendations²⁰, the rotation of the scapula around the X-s axis was defined as downward rotation being positive and upward rotation negative; rotation around the Y-s axis was defined as internal rotation being positive and external rotation negative; and rotation around the Z-s axis was defined as posterior tilt being positive and anterior tilt negative (Figs. 3A, 3B, 3C). Scapula orientation was expressed relative to the thorax using the Y-X'-Z''

sequence and humerus orientation relative to the thorax using the Y-X'-Y'' sequence in accordance with ISB recommendations²⁰. The humeral elevation angles relative to the thorax were calculated as the projection angle of each plane of elevation task using a custom Scilab version 5.5.0 code. The scapular orientation data at humerothoracic elevation angles of 30°, 60°, 90°, 120° were selected, and the amount of change from the resting position was calculated. No difference was found in gender in the average value of the rotation angle of the scapula at resting position.

Statistical analysis. For each plane of elevation, the average of five trials was analyzed. Three-way (humeral elevation angle $\times$ plane of elevation $\times$ gender) repeated measures analysis of variances (ANOVA) were used to compare the scapular rotation angles during elevation. For the statistical analysis, the level of significance was set at $P < 0.05$. Mauchly's test was used to test for sphericity, and in case of violation, the Greenhouse-Geisser correction was applied. When any significant ANOVA effects were observed, *post hoc* t-tests using the Bonferroni correction were used to determine significant differences. The statistical analysis was performed using IBM SPSS version 21 (IBM Corp., Armonk, NY, USA).

Results

Scapular upward/downward rotation. Table 1 presents the data for scapular upward and downward rotation during elevation. Both humeral elevation angle and gender showed significant main effects during elevation ($P < 0.01$), and there was a significant interaction between humeral elevation angle and gender ($P < 0.05$). No significant main effect or interaction was seen for plane of elevation.

Post hoc analysis showed that in both men and women, there were significant differences between each humeral elevation angle for all planes of elevation ($P < 0.01$, $P < 0.05$) (Figs. 4A, 3C, 3E), with the latter presenting significantly lower scapular upward angles than the former at flexion angles of 90° ($P < 0.05$) and 120° ($P < 0.01$) (Fig. 4A), scapular plane elevation of 60° ($P < 0.05$), 90°, and 120° ($P < 0.01$) (Fig. 4B), and abduction of 30°, 60° ($P < 0.05$), 90° and 120° ($P < 0.01$) (Fig. 4C).

Scapular anterior/posterior tilt. Table 2 presents the data for scapular anterior and posterior tilt during elevation. There were significant main effects for humeral elevation angle, plane of elevation, and gender ($P < 0.01$), and there was a significant interaction between humeral

Table 1. Scapular upward/downward rotation during the elevation of three planes of elevation –, upward rotation; +, downward rotation. Angles (°) are given from the resting position of the scapula and presented as mean $\pm$ SD.

		(mean $\pm$ SD)(°)			
		elevation			
		30°	60°	90°	120°
Flexion					
	Men	- 8.3 $\pm$ 2.6	- 17.0 $\pm$ 3.3	- 26.5 $\pm$ 4.1	- 34.6 $\pm$ 6.2
	Women	- 6.1 $\pm$ 3.6	- 13.2 $\pm$ 5.2	- 20.5 $\pm$ 6.2	- 28.0 $\pm$ 7.0
Scapular plane elevation					
	Men	- 7.5 $\pm$ 2.7	- 17.0 $\pm$ 3.5	- 25.8 $\pm$ 4.1	- 33.1 $\pm$ 6.2
	Women	- 5.0 $\pm$ 4.1	- 13.0 $\pm$ 4.3	- 20.0 $\pm$ 4.2	- 25.6 $\pm$ 4.2
Abduction					
	Men	- 9.3 $\pm$ 3.7	- 18.3 $\pm$ 4.8	- 26.6 $\pm$ 5.3	- 34.2 $\pm$ 6.1
	Women	- 4.2 $\pm$ 3.7	- 11.6 $\pm$ 4.2	- 18.1 $\pm$ 5.2	- 24.9 $\pm$ 5.6
Three-way repeated measures ANOVA		<i>F</i> value		<i>P</i> value	
Humeral elevation angle		283.226		$P < 0.01$	
Plane of elevation		1.032		n.s.	
Gender		90.120		$P < 0.01$	
Humeral elevation angle $\times$ Gender		2.908		$P < 0.05$	
Plane of elevation $\times$ Gender		2.094		n.s.	
Humeral elevation angle $\times$ Plane of elevation		0.200		n.s.	
Humeral elevation angle $\times$ Plane of elevation $\times$ Gender		0.017		n.s.	

n.s. : not significant

Fig. 4 Change in the scapular upward rotation angle (mean and SD) during humeral elevation.

(A) Flexion, (B) Scapular plane elevation, (C) Abduction. The graphs show the scapular upward rotation angle from the resting position during elevation for men and women. The vertical axis shows the scapular downward (+)/upward (-) rotation angle, and the horizontal axis the humeral elevation angle. Squares, men; triangles, women. The daggers indicate significant gender differences: †, $P < 0.05$; ††, $P < 0.01$. The asterisks indicate significant differences for humeral elevation: *, $P < 0.05$; **, $P < 0.01$. The humeral elevation angle and gender had significant main effects ($P < 0.01$), and there was a significant interaction between the humeral elevation angle and gender ($P < 0.05$) (Table 1).

Table 2. Scapular anterior/posterior tilt during the elevation of three planes of elevation –, anterior tilt; +, posterior tilt. Angles ($^{\circ}$) are given from the resting position of the scapula and presented as mean $\pm$ SD.

	(mean $\pm$ SD)($^{\circ}$)			
	elevation			
	30 $^{\circ}$	60 $^{\circ}$	90 $^{\circ}$	120 $^{\circ}$
Flexion				
Men	2.5 $\pm$ 2.4	4.0 $\pm$ 3.6	5.9 $\pm$ 5.5	11.9 $\pm$ 6.2
Women	1.9 $\pm$ 2.3	1.8 $\pm$ 4.1	1.3 $\pm$ 5.3	4.1 $\pm$ 5.8
Scapular plane elevation				
Men	3.3 $\pm$ 1.8	4.5 $\pm$ 2.8	6.7 $\pm$ 5.0	11.7 $\pm$ 7.1
Women	1.8 $\pm$ 2.3	2.2 $\pm$ 3.6	2.6 $\pm$ 4.4	4.9 $\pm$ 4.9
Abduction				
Men	5.1 $\pm$ 3.4	7.4 $\pm$ 4.9	10.2 $\pm$ 6.7	13.9 $\pm$ 6.7
Women	2.5 $\pm$ 2.1	4.2 $\pm$ 3.7	6.1 $\pm$ 5.3	6.9 $\pm$ 7.7
Three-way repeated measures ANOVA	<i>F</i> value		<i>P</i> value	
Humeral elevation angle	20.11		$P < 0.01$	
Plane of elevation	8.922		$P < 0.01$	
Gender	43.68		$P < 0.01$	
Humeral elevation angle $\times$ Gender	4.276		$P < 0.01$	
Plane of elevation $\times$ Gender	0.081		n.s.	
Humeral elevation angle $\times$ Plane of elevation	0.370		n.s.	
Humeral elevation angle $\times$ Plane of elevation $\times$ Gender	0.106		n.s.	

n.s. : not significant

elevation angle and gender ($P < 0.01$).

Post hoc analysis showed the following: men presented significantly increased scapular posterior tilt angles with humeral elevation angle increased for flexion, scapular plane elevation, and abduction (Figs. 5A, 5B, 5C).

Women presented significantly lower scapular posterior angles than men at flexions of 90° ($P < 0.05$) and 120° ($P < 0.01$) (Fig. 5A), at scapular plane elevation of 90° ($P < 0.05$) and 120° ($P < 0.01$) (Fig. 5B), and at abduction of 120° ($P < 0.05$) (Fig. 5C).

Scapular internal/external rotation. Table 3 presents the data for scapular internal and external rotation during elevation. The plane of elevation showed a significant main effect ($P < 0.01$), and there was a significant interaction between the plane of elevation and gender ($P < 0.05$).

Post hoc analysis showed that, the scapular external rotation angle in men was significantly greater during abduction than during flexion at a humeral elevation of 30° , 60° , and 90° and during abduction than during scapular plane elevation at a humeral elevation of 30° and 60° (Figs. 6A-C). At a humeral elevation of 60° and 90° , women presented significant differences between each plane of elevation; the scapular external rotation angle was significantly greater in abduction compared to scapular plane elevation, abduction compared to flexion, and scapular plane elevation compared to flexion (Figs. 6B and 6C), and there was significantly greater scapular external rotation angle during abduction than compared to flexion at a humeral elevation of 30° , 120° (Figs. 6A and 6D).

There was a significantly greater scapular internal rotation angle in women than in men at a flexion of 30° and 60° (Figs. 6A and 6B). No difference between men and women was seen at a humeral elevation of 90° and 120° .

Discussion

This is the first report to describe gender differences in scapular kinematics at three planes of humeral elevation. The present study revealed gender differences in scapula upward rotation and posterior tilt angles during shoulder flexion, scapular plane elevation, and abduction. Women had a significantly lower angle of upward rotation and posterior tilt than men during elevation.

The shoulder range of motion in elevation and rotation for women is significantly greater than for men¹⁷. Passive elements (tightness of the shoulder capsule and coracohumeral and glenohumeral ligaments) limit the motion of the glenohumeral joint¹⁵. The scapula and humerus are stabilized by muscle activation. A difference has been shown between healthy men and women in shoulder muscle activation, with men exhibiting superior muscle activation in the main force direction²¹. It is suggested that weaker muscle strength in women than in men may result in greater joint laxity^{15,22}. Generalized joint hyper-

mobility tests (using the Beighton Score) have shown that a higher percentage of women than men have joint laxity^{23,24}. It has also been reported that women exhibited significantly more joint laxity with an associated decrease in anterior joint stiffness compared to men²⁵. It is possible that passive and active elements around the shoulder joint influenced the results of the present study, in which women had significantly lower scapular upward rotation and posterior tilt than men during shoulder elevation. Women have greater flexibility of the glenohumeral joint than men, and the glenohumeral joint plays a greater role than the scapulothoracic joint in women during shoulder elevation. Conversely, it was clear that women in this study had less motion in the scapulothoracic joint. Gender differences in normal muscle activation patterns of the trapezius during shoulder elevation have been identified by Szucs and Borstad²⁶, with women demonstrating greater levels of activation in the upper and lower portions of the trapezius. It has been reported that the trapezius is a mobilizer as well as a stabilizer of the scapula²⁷. From the results of this study, it is speculate that the trapezius acts as a stabilizer in women. However, the details are unclear because we did not measure muscle activation simultaneously with scapular kinematics.

The present study also demonstrated that scapular internal or external rotation differed significantly according to the plane of elevation. The scapula was internally rotated during flexion, with no change compared to its resting position during scapular plane elevation, and it was externally rotated during abduction. Similar effects dependent on the plane of elevation have been described, with the scapula reportedly internally rotated by an average of 7° during flexion compared to scapular plane elevation and externally rotated by an average 7.5° during abduction compared to scapular plane elevation⁴. However, that study combined data obtained from both men and women. The present study compared men and women and showed significant differences during flexion at humeral elevations of 30° and 60° , with women having greater differences between planes of elevation. This indicates that scapular kinematics vary more markedly in women according to the plane of elevation. This cannot be explained by the fact that women have greater flexibility in the glenohumeral joint than men. An assessment of morphologic and kinematic differences showed that men have a rounder glenoid, whereas women characteristically have a glenoid that is vertically elongated²⁸. Furthermore, the humeral head is relatively large with respect to the glenoid in women²⁹. Also, as mentioned above, women have demonstrated greater levels of activation in the trapezius during shoulder elevation²⁶. Although the abovementioned morphologic and kinematic difference may be involved, the precise details accounting for gender differences remain unknown. We were unable to verify changes in the position of the scapula in this study, but we hope to do so in future research to clarify the mechanisms involved.

Fig. 5 Change in the posterior tilt angle (mean and SD) during shoulder elevation.

(A) Flexion, (B) Scapular plane elevation, (C) Abduction. The graphs show the posterior tilt angle from the resting position during shoulder elevation for men and women. The vertical axis shows the posterior (+)/anterior (−) tilt angle and the horizontal axis shows the humeral elevation angle. Squares, men; triangles, women. The daggers indicate significant gender differences: †, $P < 0.05$; ††, $P < 0.01$. The asterisks indicate significant differences for humeral elevation: *, $P < 0.05$; **, $P < 0.01$. The humeral elevation angle, plane of elevation and gender had significant main effects ($P < 0.01$), and there was a significant interaction between the humeral elevation angle and gender ($P < 0.01$) (Table 2).

Table 3. Scapular internal/external rotation during the elevation of three planes of elevation +, internal rotation; −, external rotation. Angles (°) are given from the resting position of the scapula and presented as mean $\pm$ SD.

		(mean $\pm$ SD)(°)			
		elevation			
		30°	60°	90°	120°
Flexion					
Men		0.3 $\pm$ 5.6	2.0 $\pm$ 6.7	4.3 $\pm$ 7.4	4.9 $\pm$ 8.6
Women		4.3 $\pm$ 3.2	6.8 $\pm$ 4.9	8.2 $\pm$ 5.9	7.7 $\pm$ 7.3
Scapular plane elevation					
Men		-0.9 $\pm$ 4.9	-1.5 $\pm$ 5.2	-1.2 $\pm$ 6.0	0.1 $\pm$ 8.1
Women		-0.4 $\pm$ 2.4	-0.1 $\pm$ 3.2	0.1 $\pm$ 4.5	0.1 $\pm$ 6.6
Abduction					
Men		-6.3 $\pm$ 4.9	-8.2 $\pm$ 5.4	-7.3 $\pm$ 7.2	-3.0 $\pm$ 8.6
Women		-5.1 $\pm$ 5.5	-7.4 $\pm$ 6.2	-8.5 $\pm$ 6.7	-7.9 $\pm$ 7.9
Three-way repeated measures ANOVA			<i>F</i> value	<i>P</i> value	
Humeral elevation angle			1.096	n.s.	
Plane of elevation			77.166	$P < 0.01$	
Gender			2.604	n.s.	
Humeral elevation angle $\times$ Gender			0.791	n.s.	
Plane of elevation $\times$ Gender			3.451	$P < 0.05$	
Humeral elevation angle $\times$ Plane of elevation			1.058	n.s.	
Humeral elevation angle $\times$ Plane of elevation $\times$ Gender			0.260	n.s.	

n.s. : not significant

Fig. 6 Change in the scapular internal/external rotation angle (mean and SD) during elevation.

Humeral elevation: (A) 30°, (B) 60°, (C) 90°, (D) 120°. The graphs show the internal/external rotation angle change from the resting position during elevation for men and women. The vertical axis shows the internal (+)/external (-) rotation angle, and the horizontal axis the plane of elevation. Squares, men; triangles, women. The daggers indicate significant gender differences: †, $P < 0.05$. The asterisks indicate significant differences for plane of elevation: *, $P < 0.05$; **, $P < 0.01$. The plane of elevation had a significant main effect ($P < 0.01$), and there was a significant interaction between plane of elevation angle and gender ($P < 0.05$) (Table 3).

Schwartz et al.¹⁵⁾ described that, during flexion and abduction, external rotation was significantly greater for women than for men. There were no significant gender differences for upward/downward rotation and anterior/posterior tilt. However, the present study showed that upward rotation and posterior tilt were significantly lower for women than for men during shoulder flexion, scapular plane elevation, and abduction. One possible explanation is that, in the study by Schwartz and colleagues¹⁵⁾, participant arm speeds varied during the task. Furthermore, the orientation of the humerus relative to the thorax was calculated using different rotation sequences. In the present study, consistency in the speed of the task was maintained by having participants perform each cycle of elevating and lowering the arm in 6 seconds. Sugamoto et al.⁸⁾ reported that the scapulohumeral rhythm changed according to motion speed. In that study, high- and low-speed actions consisted of cycles lasting 2 and 4 seconds

(s), respectively. The glenohumeral and scapulothoracic ratios were constant at the low, but not the high speed; and the ratios at high speed differed significantly from those at low speed. In the present study, a consistent, low-speed task was used. In contrast, the participants in the investigation by Schwartz et al.¹⁵⁾ performed a given task at their own speed which, although low, was unknown, a factor which may have affected scapular kinematics.

There were also differences in the data processing methodology. In the present study, humeral orientation was calculated using the Y-X'-Y'' sequence in accordance with ISB recommendations²⁰⁾. Schwartz et al.^{15,16)} adopted the Y-X'-Z'' sequence in order to avoid gimbal lock. Another study described the Y-X'-Y'' sequence for the humerus as being in a more anteriorly rotated and externally rotated position compared to the Y-X'-Z'' sequence, especially at lower angles of humeral elevation⁷⁾. Thus, differences in the rotation sequences may have influenced

the results.

In the present study, the task involved range of motion up to a humeral elevation of 130° starting with the arm at the side, and data was collected up to a humeral elevation of 120°. A potential problem of attaching the sensor to the skin was slipping on skin and bone. However, accurate measurement of scapular motion up to a humeral elevation of 120° is reportedly possible^{2,30)}, which is why we used this degree of elevation as the end point in the present study. Therefore, our results should be considered representative of motion to a humeral elevation of 120° or less. In future research, we expect to establish methodology for accurate measurements at greater than 120° of humeral elevation.

The present study revealed significant gender differences in scapular kinematics during shoulder flexion, scapular plane elevation, and abduction. An understanding of scapular kinematics is necessary to ensure recovery of shoulder function after injury. Previous studies have reported that scapular dyskinesis may directly cause, contribute to, or result from shoulder pain and other symptoms¹¹⁾. Ludewig et al.³¹⁾ identified significantly less scapular upward rotation in the subjects with glenohumeral instability. Furthermore, Picco et al.³²⁾ reported that women exhibited a diminished posterior tilt angle of scapula during humeral elevation, compared to men. Decreased subacromial space, which occurs more frequently in women than men, has been implicated in development of shoulder pathologies.

Our findings should be of benefit in planning of rehabilitation exercises and setting goals after injury. For example, in prioritizing rotator cuff healing after rotator cuff repair, it is important to increase scapulohumeral joint motion through early shoulder exercise. Especially in women, the possibility of repeat tear should be kept in mind, because of greater laxity of glenohumeral motion in shoulder elevation than men. During scapular plane elevation, in women and in contrast to flexion and abduction, it is unnecessary to internally or externally rotate the scapula in order to maintain the glenohumeral joint force couple. Therefore, in women, early physical therapy after surgery or injury, other than scapular plane motion, should be undertaken while paying attention to glenohumeral force coupling. If rehabilitation is done without considering gender differences, there is a possibility of delay in recovery. In future investigations analyzing various tasks, it is necessary to establish gender-specific shoulder training guidelines.

The main limitation of this study was the small sample size within a narrow age range. Our participants were all young, in their 20s and 30s. There were no high-performance athletes or people who undertook heavy manual work. Secondly, it was impossible to exclude the possibility that the observed angular differences were due to significant differences in participants' height and weight. Furthermore, differences in thoracic alignment may also

have influenced the results. This study only analyzed active motion, and the influence of joint laxity remains unknown. Further studies should complete passive motion analyses. Determination of the mechanisms causing scapular dyskinesis will require further study that takes the above factors into consideration during participant selection.

Conclusions

This study investigated three-dimensional scapular kinematics during shoulder flexion, scapular plane elevation, and abduction during elevation, comparing men and women. Scapular upward rotation and posterior tilt angles significantly increased with each humeral elevation angle, with women exhibiting lower angles than men. Scapular internal or external rotation also differed significantly according to the plane of elevation, with the scapula internally rotated during flexion, unchanged from the resting position during scapular plane elevation, and externally rotated during abduction. This feature of variation according to the plane of elevation was more marked for women. Our findings could be of benefit in establishing gender-specific shoulder training guidelines.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this article.

Acknowledgments

The authors would like to thank the staff of Niigata Central Hospital who participated in this study.

References

- 1) Itoi E, Hsu HC and An KN. 1996. Biomechanical investigation of the glenohumeral joint. *J Shoulder Elbow Surg* 5: 407-424.
- 2) Karduna AR, McClure PW and Michener LA. 2000. Scapular kinematics: effects of altering the Euler angle sequence of rotations. *J Biomech* 33: 1063-1068. doi: 10.1016/S0021-9290(00)00078-6.
- 3) Lee SK, Yang DS, Kim HY and Choy WS. 2013. A comparison of 3D scapular kinematics between dominant and non-dominant shoulders during multiplanar arm motion. *Indian J Orthop* 47: 135-142. doi: 10.4103/0019-5413.108882.
- 4) Ludewig PM, Phadke V, Braman JP, Hassett DR, Cieminski CJ and LaPrade RF. 2009. Motion of the shoulder complex during multiplanar humeral elevation. *J Bone Joint Surg Am* 91: 378-389. doi: 10.2106/JBJS.G.01483.
- 5) Matsuki K, Matsuki KO, Mu S, Yamaguchi S, Ochiai N, Sasho T, Sugaya H, Toyone, T, Wada Y, Takahashi K and Banks SA. 2011. In vivo 3-dimensional analysis of scapular kinematics: comparison of dominant and nondominant shoulders. *J Shoulder Elbow Surg* 20: 659-665. doi: 10.1016/j.jse.2010.09.012.

- 6) McClure PW, Michener LA and Karduna AR. 2006. Shoulder function and 3-dimensional scapular kinematics in people with and without shoulder impingement syndrome. *Phys Ther* 86: 1075-1090.
- 7) Phadke V, Braman JP, LaPrade RF and Ludewig PM. 2011. Comparison of glenohumeral motion using different rotation sequences. *J Biomech* 44: 700-705. doi: 10.1016/j.jbiomech.2010.10.042.
- 8) Sugamoto K, Harada J, Machida A, Inui H, Miyamoto T, Takeuchi E, Yoshikawa H and Ochi T. 2002. Scapulohumeral rhythm: relationship between motion velocity and rhythm. *Clin Orthop Relat Res* 119-124.
- 9) Forte FC, de Castro MP, de Toledo JM, Ribeiro DC and Loss JF. 2009. Scapular kinematics and scapulohumeral rhythm during resisted shoulder abduction - implications for clinical practice. *Phys Ther Sport* 10: 105-111. doi: 10.1016/j.ptsp.2009.05.005.
- 10) Ichihashi N, Ibuki S, Otsuka N, Takashima S and Matsumura A. 2014. Kinematic characteristics of the scapula and clavicle during military press exercise and shoulder flexion. *J Shoulder Elbow Surg* 23: 649-657. doi: 10.1016/j.jse.2013.11.014.
- 11) Kibler WB and Sciascia A. 2016. The role of the scapula in preventing and treating shoulder instability. *Knee Surg Sports Traumatol Arthrosc* 24: 390-397. doi: 10.1007/s00167-015-3736-z.
- 12) Borstad J and Ludewig PM. 2002. Comparison of scapular kinematics between elevation and lowering of the arm in the scapular plane. *Clinical Biomechanics* 17: 650-659. doi: 10.1016/S0268-0033(02)00136-5.
- 13) Yano Y, Hamada J, Tamai K, Yoshizaki K, Sahara R, Fujiwara T and Nohara Y. 2010. Different scapular kinematics in healthy subjects during arm elevation and lowering: glenohumeral and scapulothoracic patterns. *J Shoulder Elbow Surg* 19: 209-215. doi: 10.1016/j.jse.2009.09.007.
- 14) Habechian FA, Rosa DP, Haik MN and Camargo PR. 2016. Sex-related differences in scapular kinematics during elevation of the arm in asymptomatic children and adults. *J Appl Biomech* 32: 513-519. doi: 10.1123/jab.2015-0341.
- 15) Schwartz C, Croiser JL, Rigaux E, Bröls O, Denoël V and Forthomme B. 2016. Gender effect on the scapular 3D posture and kinematic in healthy subjects. *Clin Physiol Funct Imaging* 36: 188-196. doi: 10.1111/cpf.12212.
- 16) Schwartz C, Croisier JL, Rigaux E, Denoël V, Bröls O and Forthomme B. 2014. Dominance effect on scapula 3-dimensional posture and kinematics in healthy male and female populations. *J Shoulder Elbow Surg* 23: 873-881. doi: 10.1016/j.jse.2013.08.020.
- 17) Barnes CJ, Van Steyn SJ and Fischer RA. 2001. The effects of age, sex, and shoulder dominance on range of motion of the shoulder. *J Shoulder Elbow Surg* 10: 242-246. doi: 10.1067/mse.2001.115270.
- 18) McQuade KJ, Borstad J and de Oliveira AS. 2016. Critical theoretical perspective on scapular stabilization: what does it really mean, and are we on the right track? *Phys Ther* 96: 1162-1169.
- 19) Ozaki J and Kawamura I. 1984. "Zero-position" Functional shoulder orthosis for postoperative management of rotator cuff injuries. *Orthosis and Prosthetics* 38: 66-68.
- 20) Wu G, van der Helm FC, Veeger HE, Makhssous M, Van Roy P, Anglin C, Nagels J, Karduna AP, McQuade K, Wang X, Werner FW and Buchholz B. 2005. 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* 38: 981-992. doi: 10.1016/j.jbiomech.2004.05.042.
- 21) Anders C, Bretschneider S, Bernsdorf A, Erler K and Schneider W. 2004. Activation of shoulder muscles in healthy men and women under isometric conditions. *J Electromyogr Kinesiol* 14: 699-707. doi: 10.1016/j.jelekin.2004.04.003.
- 22) Stoll T, Huber E, Seifert B, Michel BA and Stucki G. 2000. Maximal isometric muscle strength normative values and gender-specific relation to age. *Clin Rheumatol* 19: 105-113.
- 23) Cameron KL, Duffy ML, DeBerardino TM, Stoneman PD, Jones CJ and Owens BD. 2010. Association of generalized joint hypermobility with a history of glenohumeral joint instability. *J Athl Train* 45: 253-258. doi: 10.4085/1062-6050-45.3.253.
- 24) Wolf JM, Cameron KL and Owens BD. 2011. Impact of joint laxity and hypermobility on the musculoskeletal system. *J Am Acad Orthop Surg* 19: 463-471.
- 25) Borsa PA, Sauers EL and Herling DE. 2000. Patterns of glenohumeral joint laxity and stiffness in healthy men and women. *Med Sci Sports Exerc* 32: 1685-1690.
- 26) Szucs KA and Borstad JD. 2013. Gender difference between muscle activation and onset timing of four subdivisions of trapezius during humerothoracic elevation. *Hum Mov Sci* 32: 1288-1298. doi: 10.1016/j.humov.2013.05.003.
- 27) Johnson G, Bogduk N, Nowitzke A and House D. 1994. Anatomy and actions of the trapezius muscle. *J Clin Biomech* 9: 44-55.
- 28) Merrill A, Guzman K and Miller SL. 2009. Gender differences in glenoid anatomy: an anatomic study. *Surg Radiol Anat* 31: 183-189. doi: 10.1007/s00276-008-0425-3.
- 29) Matsumura N, Oki S, Ogawa K, Iwamoto T, Ochi K, Sato K and Nagura T. 2016. Three-dimensional anthropometric analysis of the glenohumeral joint in a normal Japanese population. *J Shoulder Elbow Surg* 25: 493-501. doi: 10.1016/j.jse.2015.08.003.
- 30) McClure PW, Michener LA, Sennett BJ and Karduna AR. 2001. Direct 3-dimensional measurement of scapular kinematics during dynamic movements in vivo. *J Shoulder Elbow Surg* 10: 269-277. doi: 10.1067/mse.2001.112954.
- 31) Ludewig PM and Reynolds JF. 2009. The association of scapular kinematics and glenohumeral joint pathologies. *J Orthop Sports Phys Ther* 39: 90-104. doi: 10.2519/jsopt.2009.2808.
- 32) Picco BR, Vidt ME and Dickerson CR. 2017. Scapular kinematics by sex across elevation planes. *J Appl Biomech* 1: 1-39. doi: 10.1123/jab.2017-0082.