TAL AMASAY, PhD[1] • ANDREW R KARDUNA, PhD[2]

Scapular Kinematics in Constrained and Functional Upper Extremity Movements

Shoulder movements have been investigated with respect to many applications, including sports performance, workplace design, and clinical intervention. Within this area of research it is well established that proper arm elevation is the result of the interaction between the glenohumeral and scapulothoracic joints. The scapula serves as a stable base for the glenohumeral joint and contributes to arm elevation. Altered scapular position and/or orientation may interfere with optimal shoulder coordination.[19] Abnormal scapulothoracic joint motion has been associated with pathologies such as instability,[22] frozen shoulder,[35,36] and shoulder impingement.[19]

Many studies have evaluated scapulothoracic joint kinematics and the role it plays in different patient populations. Constrained protocols are commonly used in the measurement of shoulder kinematics. Four main methods were identified in the literature that have been used to constrain shoulder movement: (1) measuring scapulothoracic joint position at different static humeral elevation angles[9,17,33]; (2) constraining shoulder movement to a specific plane of motion, typically the frontal, sagittal, or scapular planes[4,23,31]; (3) restricting joint (other than the shoulder) or segment motion by instructing the subject to hold the position of specific segments during motion, such as extending their elbow[25,27]; and (4) restricting motion using a specially designed apparatus or splint,[12,26,44] or any combination of the above options. However, few studies have measured scapulothoracic joint kinematics in functional scenarios, such as during wheelchair propulsion and transfer activities,[8,29,34] and during activities of daily living, such as reaching, perineal care, hair combing, and eating.[13,14,21,43]

To the best of our knowledge, there is only 1 published study[21] that has compared scapular kinematics between constrained and functional humeral movements. However, this study made the comparison only at the end position of a hair-combing task, which did not describe scapular kinematics through the whole movement. To evaluate functional lower extremity motion, gait analysis is commonly used. However, there is no single agreed-upon functional-testing protocol to evaluate shoulder kinematics

• **STUDY DESIGN:** Controlled laboratory study using a single-group, repeated-measures design.

• **OBJECTIVES:** To investigate scapular kinematics during both constrained and functional shoulder movements.

• **BACKGROUND:** Abnormal scapulothoracic joint motion has been associated with pathologies such as shoulder impingement. Constrained protocols are commonly used in the measurement of shoulder kinematics; however, few studies have measured motion during functional tasks.

• **METHODS:** Twenty-five healthy subjects participated in this study. Three-dimensional kinematic data from the scapula and humerus with respect to the thorax were collected with a magnetic tracking system. Functional testing consisted of 6 different tasks representing common activities of daily living. Constrained testing consisted of at least 42 arm elevations in various planes. Two-way analyses of variance with repeated measures were used to compare scapular rotations between constrained and functional movements at the same humeral elevation and plane of elevation angles. Intersubject variability was compared between the overhead tasks and the constrained humeral elevation in the scapular plane by using the coefficient of multiple correlations.

• **RESULTS:** Significant differences between constrained trials and functional tasks were found for all scapular rotations. A similar pattern was observed for scapular rotations variability between overhead tasks and constrained arm elevation in the scapular plane.

• **CONCLUSION:** Care needs to be taken when comparing and generalizing scapular kinematic data from constrained humeral movements and applying it to functional humeral movements. *J Orthop Sports Phys Ther 2009;39(8):618-627. doi:10.2519/jospt.2009.2788*

• **KEY WORDS:** *scapula, scapulothoracic joint, shoulder biomechanics, unconstrained movement*

[1]Assistant Professor, Department of Sport and Exercise Sciences, School of Human Performance and Leisure Sciences, Barry University, Miami Shores, FL. [2]Associate Professor, Department of Human Physiology, University of Oregon, Eugene, OR. The study protocol was approved by The Institutional Review Board of the University of Oregon. Address correspondence to Dr Andrew R. Karduna, Department of Human Physiology, University of Oregon, Eugene, OR 97403. E-mail: karduna@uoregon.edu

in healthy and nonhealthy subjects. The most common testing protocol for evaluating shoulder kinematics is constrained scapular plane of elevation.

The purpose of the present study is to compare scapular kinematics during constrained and functional shoulder movements. In the present study, shoulder movement was constrained using methods 2 and 3 mentioned previously: constraining shoulder movement to a specific plane and restricting joint motion by instructing the subject to hold the position of the elbow and trunk. This led us to consider the following research questions: (1) What are the differences in scapular orientation between constrained and functional tasks at specific humeral orientations, and (2) is the intersubject variability smaller during constrained scapular-plane arm elevation when compared to overhead functional tasks?

METHODS

Subjects

Twenty-five healthy subjects (12 males, 13 females) participated in this study: mean age (SD), 25.8 (6.4) years; height, 1.74 (0.08) m; body mass, 70.1 (21.9) kg. The University of Oregon Institutional Review Board approved the protocol for this study and subject consent was obtained prior to data collection. The inclusion criteria were no prior shoulder surgery and no shoulder injury that required rehabilitation in the previous 2 years. All participants were right handed. They had no limitation in humeral elevation range of motion and did not suffer from any known neurological problems. They were instructed not to perform heavy upper-body exercises in the 24 hours prior to testing.

Instrumentation

Three-dimensional kinematic data from the scapula, humerus, and thorax were collected via the Liberty magnetic tracking system (Polhemus, Colchester, VT), which consisted of an electronics unit, transmitter, 3 sensors, and 1 digitizer. This system was interfaced with the MotionMonitor software program (Innovative Sports Training, Chicago, IL). Data were collected at a rate of 120 Hz per sensor. The transmitter emitted an electromagnetic field that was detected by the digitizer and the sensors. The system's electronic unit determined the relative orientation and position of the sensors in space. Data analysis was performed with LabView software (National Instruments, Austin, TX).

Setup and Digitization

Three sensors were placed on each subject. A thoracic sensor was attached using double-sided adhesive tape to the manubrium just below the jugular notch, then secured in place with adhesive tape. A humeral sensor was placed on the humerus over the deltoid tuberosity using a customized molded cuff attached by Velcro strips. A scapular tracker, previously validated in our lab, was used to quantify scapular kinematics. The root-mean-square (RMS) error associated with the scapular tracker for scapular posterior tilt, upward rotation, and external rotation was reported to be 6.2°, 4.5°, and 5.0°, respectively.[11] Plastic screws secured a sensor to the scapular tracker jig. The jig was attached atop the spine of the scapula and acromial process, using adhesive Velcro strips. This method of measuring scapular kinematics has previously demonstrated good reliability, with intraclass correlation coefficients ($ICC_{3,1}$) values higher than 0.9 and standard error of measurement (SEM) values ranging from 1° to 2.6°.[41] A global coordinate system was established by mounting the transmitter on a rigid plastic base. The transmitter was located behind the tested arm at the humeral sensor height at a horizontal distance of 30 cm from the trunk. A foot alignment device was used to determine each participant's preferred foot position during digitization (**FIGURE 1**). This device was used later to reposition the participants at their initial preferred position after each rest period.

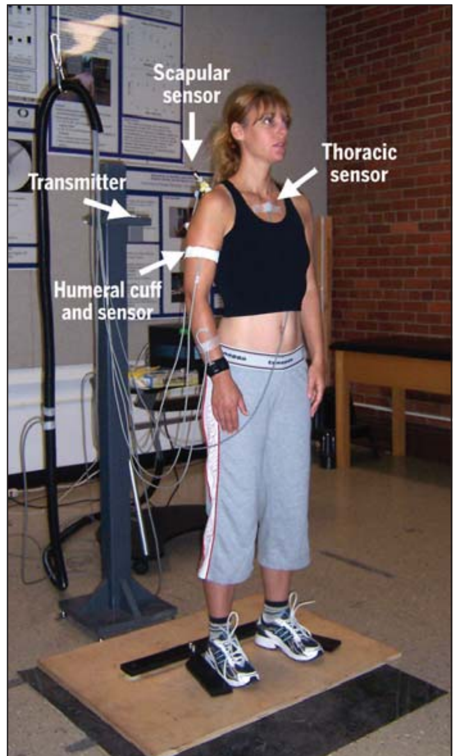

FIGURE 1. Study setup and sensors placement. Note that the forearm sensor is not related to the present study.

Anthropometrical measurements were taken from each participant using a measuring tape. Upper extremity length was measured from the anterior aspect of the acromial process to the tip of the middle finger, with the elbow extended at the sides and the participant in a seated position.[13] Shoulder height was measured from the anterior aspect of the acromion to the ground. Body height was measured from the head apex to the ground. Shoulder width was measured from the lateral aspect of the left acromion to the lateral aspect of the right acromion. The later 3 measurements were made with subjects standing in their natural posture.

Throughout digitization and data collection, participants were in their natural standing position. The following landmarks were digitized on the thorax (T8, xiphoid process, C7, and jugular notch), scapula (root of spine of the scapula, acromial angle, and inferior angle), humerus (medial and lateral epicondyles), and ulna (ulnar styloid process). The arbitrary axes defined by the magnetic tracking system were converted to anatomically appropriate embedded axes derived from the digitized bony landmarks, based on the International Society of Biomechanics recommendation for the upper extremity.[46] All landmarks were surface points and, therefore, could be located directly, except for the center of the humeral head. The center of the humeral head was defined as the point on the humerus that moved the least with respect to the scapula while moving the humerus through short arcs (less than 45°) of mid-range glenohumeral motion and was calculated using a least-squares algorithm.[42] After the digitization process, raw data from the sensors were converted into anatomically defined rotations that could be displayed in real time using the MotionMonitor software. Standard matrix transformation methods were used to determine the rotational matrix of the humerus and scapula with respect to the thorax. For the humerus, the International Society of Biomechanics (ISB) second recommendation was used, taking the ulnar styloid process as the third point for the plane, with the elbow in 90° of flexion.[46] Humeral rotations were represented using a standard Euler angle sequence (Y-X'-Y''), in which the first rotation defined the plane of elevation, the second rotation described the amount of elevation, and the last rotation represented the amount of internal/external rotation. Scapular rotations were represented using an Euler angle sequence (Y-X'-Z'') of external/internal rotation, upward/downward rotation, and anterior/posterior tilting. Description and figure of these scapular rotations can be found in a recent manuscript by Ludewig and Reynolds.[18]

FIGURE 2. Motions performed by the subjects: (A) belt, (B) shelf, (C) reach out, (D) object right, (E) object left, (F) overhead, (G) constrained trial at 60° to 80° range.

Experimental Procedure

Participants started the experiment with a standardized warm-up procedure, which included Codman's pendulums and stretches for the rotator cuff muscles. To perform Codman's pendulum, the subjects leaned forward at the hip while supporting their body with the nondominant arm on a table and holding a 1.1-kg mass in their dominant hand. Each subject performed a set of 15 repetitions of arm circles, clockwise and counterclockwise, followed by a set of 15 repetitions of a back-and-forth movement in the sagittal plane. The stretches consisted of holding a static external rotation and then internal rotation position while the shoulder was abducted in the frontal plane to approximately 90°, for 2 sets of 15 seconds each.[39] Data collection followed, first with the functional tasks and then the constrained trials. This set sequence of testing was based on pilot data collection revealing that subjects altered the way they reached to the different functional targets when the constrained trials were introduced first. All testing was completed in a single session and performed on the dominant upper extremity.

The functional testing protocol consisted of 6 tasks. These tasks represented activities of daily living, with an attempt to cover a wide range of different humeral planes of elevation and elevations. Several of the tasks presented by Lin et al[13] were modified based on pilot data, because their subjects were in a seated position (as opposed to standing in the present study). Participants practiced each motion as often as necessary to become comfortable with the task. They were instructed not to move their feet during all tasks. Functional task descriptions and locations were as follows: (1) reaching to a seat belt (belt) in the frontal plane at a horizontal distance of 75% of arm length at shoulder height; (2) reaching to a shelf (shelf) in the sagittal plane at a horizontal distance of 80% of arm length and height of 50% of arm length above shoulder height; (3) reaching out (reach out) in the sagittal plane at a horizontal distance of 120% of arm length and height of 66% of arm length below shoulder height; (4) reaching to an object on the right side (object right) in the frontal plane at a horizontal distance of 66% of arm length and height of 66% of arm length below shoulder height; (5) reaching to an object on the left side (object left) in the frontal plane, at a horizontal distance of 50% of arm length and height of 66% of arm length below shoulder height; (6) reaching to an imaginary point above their head (overhead). For the first 5 tasks the instructions were to reach to the target, which was a small plastic object (negligible weight) on a shelf, and bring it back to the side of the body. For the sixth task they were instructed to reach as high as possible (**FIGURE 2**). All target locations were normalized based on the participant's anthropometric data, and task order was randomized.

After performing the functional tasks, each participant performed constrained arm elevations in various planes ranging from 0° (frontal plane) to 120°, where 90° represented the sagittal plane. This range was divided into 6 different trials of 20° intervals, each starting at a different plane of elevation angle (0°, 20°, 40°, 60°, 80°, and 100°). Each trial consisted of 7 constrained arm elevation and depression movements. Subjects were instructed to elevate and lower their arm along the path of a series of 7 equally distributed vertical lines secured to a mobile 0.6 × 1.9-m board. These lines were spaced at approximately 3° increments of plane of elevation. Participants were instructed to keep their elbow extended and thumb pointing up and to elevate their arm as high as possible, restricting trunk and foot movements (**FIGURE 2**). Participants elevated and lowered their arms to the count of 8 beeps from a metronome set at 84 beeps per minute. This resulted in an average angular velocity across all participants of approximately 40°/s. Participants practiced each motion as often as necessary to become comfortable with the trial. During all trials, the researcher closely observed the participants' arm motion and trunk position and verbally instructed them to keep the desired arm and trunk positions. After each trial, the participants rested for 3 minutes. The order of these trials was randomized. After 6 trials, which consisted of a total of 42 constrained arm elevations, the functional task data were plotted against the constrained data to compare humeral plane of elevation and humeral elevation. Data were visually inspected to ensure that most of the points of the functional tasks were encompassed in the area of the constrained trials. If a gap of 10° or higher in plane of elevation was identified within the constrained data, the participant performed another constrained trial in this range, which increased the total constrained arm elevations to 49.

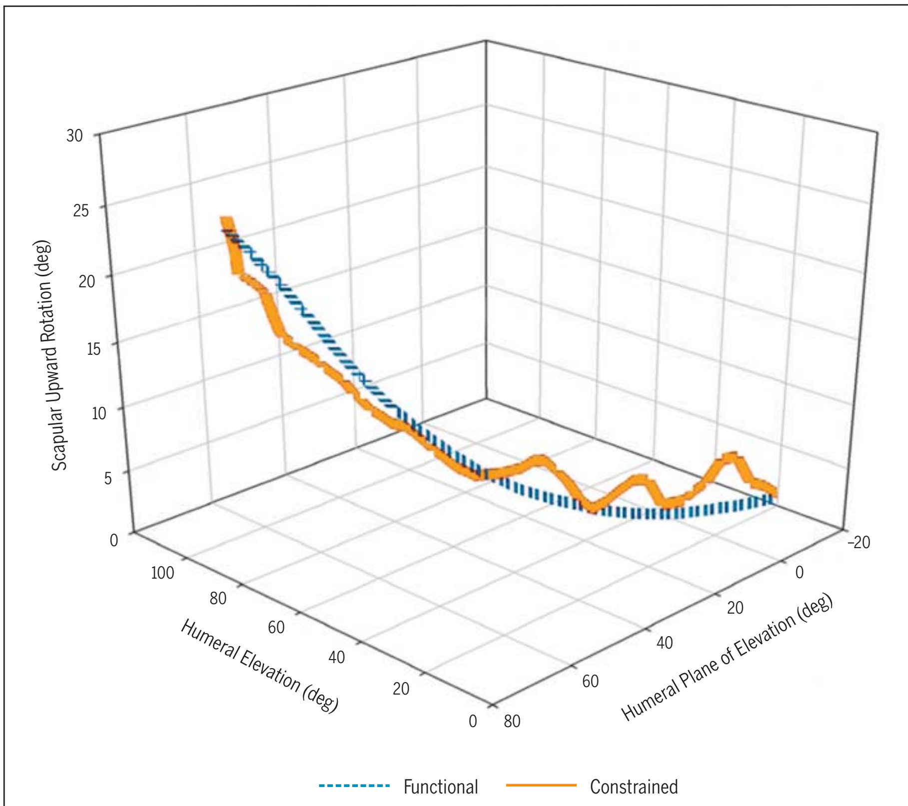

FIGURE 3. Representative 3-dimensional representation of the functional shelf task and its corresponding interpolated constrained data.

Data Reduction and Analysis

Before data analysis, all files were trimmed below 20° of humeral elevation angle (to avoid Gimble Lock) and above 120° of humeral elevation angle (to minimize skin slippage error of the scapula tracker).[11] For presentation purposes, scapular upward rotation and humeral elevation angles were multiplied by –1. A correction equation, previously used in our lab,[11] was used to correct scapular upward rotation for the constrained and functional data, which further reduced skin movement artifact. The constrained data were matched to the functional data based on humeral elevation and humeral plane of elevation angles for each participant using a customized LabView program. For each constrained arm elevation, scapular angles were linearly interpolated in 0.1° increments of humeral elevation angles, to increase humeral elevation angle resolution. Based on the sampling frequency (120 Hz) and the estimated arm elevation velocity of 40°/s, arm elevation will change in an average increment of 0.3°. Hence, a linear interpolation of 0.1° would not result in an unreasonable distortion of the data. Next, for each data point for the functional motions, the corresponding data points from the constrained motions with the same humeral elevation angle were identified. From all the matching humeral elevation constrained points, 2 data points that encompassed the cor-

TABLE 1 **Scapular Angles for Functional and Constrained Shoulder Motion at Specific Humeral Elevation Angles During Specific Tasks***

Tasks	Humeral Elevation	External Rotation (deg)		Upward Rotation (deg)		Posterior Tilt (deg)	
		Functional	Constrained	Functional	Constrained	Functional	Constrained
Belt	30°	32.2 (7.0)	33.3 (7.5)	1.0 (4.9)†	−6.4 (4.9)	−9.5 (7.7)†	−11.1 (8.2)
	60°	38.8 (7.4)	39.7 (6.9)	12.9 (7.9)†	5.5 (6.8)	−8.8 (7.7)	−10.7 (6.9)
Shelf	30°	27.2 (7.3)†	29.5 (8.4)	0.4 (4.7)†	−5.9 (4.7)	−9.5 (7.5)	−10.4 (8.3)
	60°	29.2 (7.8)†	33.7 (8.8)	10.7 (5.1)†	2.5 (5.7)	−6.0 (8.1)†	−8.3 (8.4)
	90°	34.5 (8.6)†	37.2 (10.1)	24.4 (5.8)†	16.6 (6.8)	−4.4 (7.8)	−6.6 (8.7)
Reach out	30°	35.5 (6.9)†	30.6 (7.9)	−10.6 (5.7)†	−5.2 (5.1)	−12.3 (6.7)†	−10.7 (8.9)
	60°	41.9 (8.0)†	35.5 (11.0)	−3.2 (10.3)†	6.0 (9.0)	−10.9 (5.1)	−10.2 (7.7)
Object right	30°	27.1 (7.4)†	22.2 (7.7)	−8.6 (8.0)†	−3.0 (8.4)	−11.5 (6.2)†	−9.2 (5.8)
Object left	30°	36.1 (6.5)†	33.7 (6.7)	−5.8 (8.2)	−3.7 (7.8)	−13.8 (4.9)†	−12.1 (4.2)
Overhead	30°	25.4 (9.9)†	27.9 (10.2)	1.6 (3.9)†	−4.9 (4.6)	−8.2 (7.8)	−8.1 (7.4)
	60°	25.7 (10.7)†	31.6 (10.4)	13.6 (4.5)†	3.9 (5.4)	−4.4 (8.6)†	−6.4 (8.4)
	90°	27.4 (11.2)†	32.9 (11.8)	26.9 (4.5)†	17.8 (6.2)	−1.6 (8.9)†	−4.8 (8.5)
	120°	31.4 (13.4)	29.2 (12.6)	39.8 (4.2)†	34.4 (4.0)	−1.3 (10.3)	−2.4 (10.0)

* *Data are means (SD).*
† *Statistically significant differences between the functional and constrained conditions* $P<.05$.

responding functional humeral plane of elevation angle were selected. These constrained planes of elevation angles were linearly interpolated to match their corresponding functional task plane of elevation angle. This algorithm was used to interpolate all 3 scapular angles. For example, consider a functional data point at 30.3° elevation in the 46.2° plane. To find a corresponding point from the constrained data, interpolation might have been performed between the following 2 points: 30.3° elevation in the 45.1° plane and 30.3° elevation in the 48.2° plane. Note, that the elevation angles matched exactly, so for this process the interpolation is for the plane of elevation angles. With this procedure, for every data point of the functional protocol there was a corresponding interpolated constrained data point at the same humeral elevation and plane of elevation angles (**FIGURE 3**).

Statistical analysis was performed using SPSS, Version 15 (SPSS, Chicago, IL). A series of 2-way, repeated-measures analyses of variance (ANOVAs) were conducted with 1 dependent variable (scapular angles) and 2 within-subject factors: condition (constrained and functional) and position (30°, 60°, 90°, and 120° of humeral elevation angles). When significant interactions were found between the condition and the position, a post hoc Bonferroni-Holm procedure was used.[45]

For each task, scapular angles differences (between the functional data and the interpolated constrained data) were calculated, averaged between participants and plotted. These graphs were searched for patterns that could explain the differences in scapular orientations as a function of humeral elevation angle. Positive differences in scapular angles represent functional angles that were larger than constrained angles.

For each subject the raw constrained data were searched to identify the specific arm elevation that was performed in the scapular plane. The scapular plane was identified as the arm elevation closest to 35° of plane of elevation at 90° of humeral elevation (mean ± SD, 35.0° ± 0.8°). Out of the 6 functional tasks, the shelf and overhead tasks were the only 2 that involved overhead motion. Intersubject variability was compared between the functional tasks and the constrained humeral elevation by using the coefficient of multiple correlation (CMC) comparing the estimated variance in each of the scapular angles (equation 1). The CMC value reflects the intersubject variability of the waveforms. The CMC has been used to evaluate the similarity between waveforms in gait analysis[10,38] shoulder[20] and scapular motion.[40] When the waveforms are similar, the CMC value (R^2) is close to 1; when the waveforms are dissimilar, the CMC value is close to 0. This expression yielded a measure of waveform repeatability.[30]

$$R^2 = 1 - \frac{\sum_{i=1}^{P}\sum_{j=1}^{N}(Y_{ij} - \bar{Y}_i)^2}{\sum_{i=1}^{P}\sum_{j=1}^{N}(Y_{ij} - \bar{Y})^2}$$

EQUATION 1

i is humeral elevation angle, j is subject-specific scapular angle, P is the number of elevation angles increments, N is the number of subjects, Y_{ij} is a subject-specific scapular angle at specific humeral elevation, $\bar{Y}_i$ is the average scapular angle between subjects at a specific humeral elevation angle, and $\bar{Y}$ is the total average

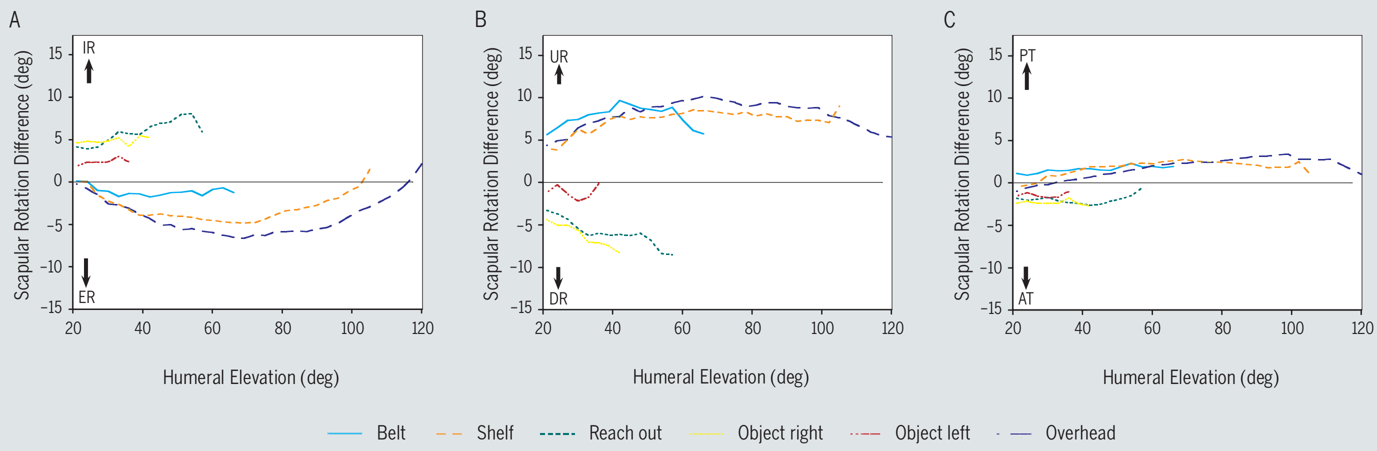

FIGURE 4. Mean scapular angle differences for the interpolated constrained data and functional tasks as a function of humeral elevation angle for (A) scapular internal/external rotation (IR/ER), (B) scapular upward/downward rotation (UR/DR), and (C) scapular posterior/anterior tilt (PT/AT).

of the scapular angle at all elevation angle for all subjects.

For both of the overhead functional tasks and the scapular plane elevation motion, the average and standard deviation of scapular upward rotation angles were plotted at specific humeral elevation angle.

TABLE 2 Intersubject Scapular Orientation Coefficient of Multiple Correlation Between Overhead Functional Tasks and Constrained Arm Movement in the Scapular Plane

	Internal Rotation	Upward Rotation	Posterior Tilt
Constrained	0.11	0.69	0.33
Shelf	0.20	0.66	0.38
Overhead	0.18	0.82	0.57

RESULTS

The first goal of this study was to compare scapular orientation between constrained and functional shoulder motion. The statistical analysis revealed significant condition-by-position interactions for all scapular rotations ($P<.05$). A post hoc Bonferroni-Holm test found significant differences in most of the cases in scapular angles between conditions for all the tasks (**TABLE 1**). For scapular external rotation, a maximum average angle difference of 6.4° was found in the reach-out task at 60° of humeral elevation. For scapular upward rotation, a maximum average angle difference of 9.7° was found in the overhead task at 60° of humeral elevation. While, for scapular posterior tilting, a maximum average angle difference of 3.2° was found in the overhead task at 90° of humeral elevation.

To help identify patterns of differences between the constrained and functional scapular data, the data were averaged based on humeral elevation angles (**FIGURE 4**). Evaluation of these curves revealed that the scapular angle differences during the reach out, object right, and object left tasks had the same general shape, with larger scapular angles for the functional data in scapular external rotation, and larger scapular angles for the constrained data in scapular upward rotation and posterior tilt. Opposite patterns were observed for the belt, shelf, and overhead tasks.

The second goal of this study was to compare intersubject variability between overhead functional tasks and constrained arm elevation in the scapular plane. The CMC values showed that the scapular orientation variability between the overhead functional tasks and the constrained arm elevation in the scapular plane were similar (**TABLE 2**). The shape and the standard deviation of scapular upward rotation were found to be similar for the 3 different shoulder motions (**FIGURE 5**).

DISCUSSION

The present study compared scapular behavior between 2 conditions: constrained and functional shoulder motions. Six functional tasks were compared covering a wide combination of humeral elevation and plane of elevation angles. Similarly, constrained arm elevation covered a wide range of planes of elevation. The comparison of scapular motion between the 2 conditions was performed at the same humeral elevation and humeral plane of elevation angles.

Significant differences were noted in the means found for most conditions. Scapular upward rotation had the highest mean differences. Scapular posterior tilt had fewer significant differences, which may be related to its relatively small range of motion. However, these differences are

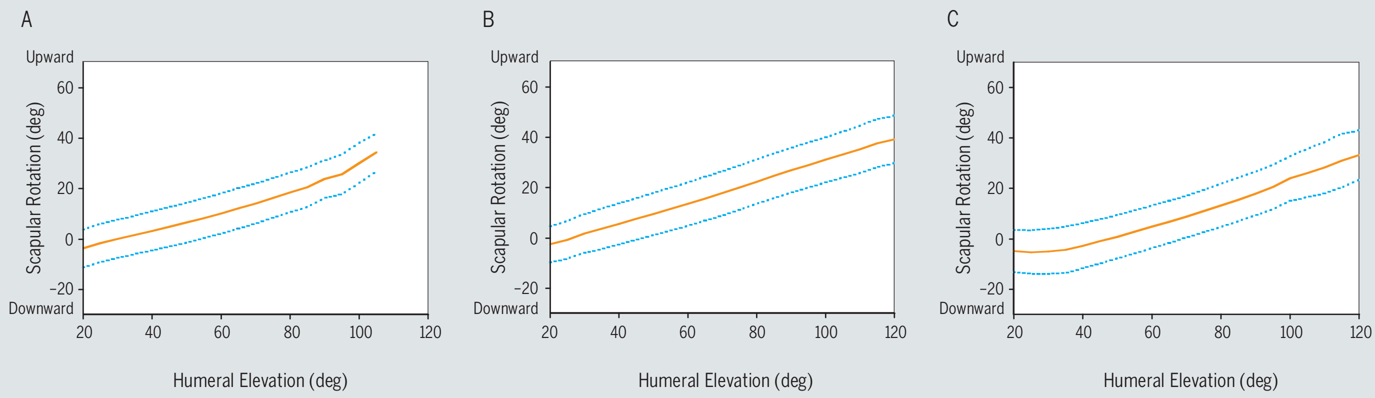

FIGURE 5. Mean and standard deviation of scapular upward rotation as a function of humeral elevation for: (A) shelf task, (B) overhead task, and (C) constrained elevation in the scapular plane.

absolute differences. The relative difference in scapular angles is the ratio between the observed differences and the total range of motion of the corresponding functional task. The highest ratio value of 1.6 (160%) was found for scapular upward rotation during object right task. The reach-out task had the second highest ratio value of 1.2 (120%) for scapular upward rotation. However, in general, the overhead, shelf, belt, and object left tasks had lower ratio values. These findings suggest that the differences between the constrained and functional protocols were higher for the object right and reach out tasks. For these tasks, the mean upward rotation ranges of motion were the smallest for reach out and object right (7.8° and 3.6°, respectively), followed by object left task with 22.5°. These small ranges of motion of upward rotation may have influenced subject control on movement execution. It should be noted that in our previous reliability study of this methodology, values for the SEM were as high as 2.6°. Therefore, differences between constrained and functional data in the present study that are lower than this upper bound might be due to measurement error.

From a clinical perspective, it has been shown that subjects who have pathologies such as impingement and frozen shoulder have altered scapular kinematics. The average differences between asymptomatic and symptomatic groups reported in the literature ranges from 3.8° to 7.7° for scapular upward rotation,[2,16,24,35] 3.3° to 9.5° for scapular posterior tilt,[2,16,19,24] and 4.4° to 5.2° for scapular external rotation.[16] Similar magnitude differences were found in the current study between constrained and functional motion.

To further investigate scapular angle differences, a comparison of the average angle differences between the constrained and functional humeral motion was performed (**FIGURE 4**). The 6 tasks can be divided into 2 groups. The first group (group 1) consisted of belt, shelf, and overhead tasks, and the second group (group 2) consisted of reach out, object right, and object left tasks. Throughout most of scapular internal rotation, constrained angles were found to be larger than the functional angles in group 1. However, the opposite pattern was observed in group 2. Most scapular upward rotation and posterior tilt functional angles were larger than the constrained angles in group 1, whereas, the opposite was true in group 2. Group 1 had a larger range of humeral elevation angle relative to group 2. This may indicate that functional tasks with a target lower than shoulder height may have different muscle recruitment and coordination patterns than functional tasks with a target above shoulder height. Sainburg et al[37] found that when reaching to the same end point target from different starting locations, the path was similar but muscle recruitment and coordination patterns were different.

Pearl et al[32] found that when naturally reaching overhead, humeral elevation was preferentially executed in the scapular plane. The most common test for shoulder behavior utilized constrained humeral elevation, typically in the scapular plane.[1,3,5] One question we were interested in answering was whether arm elevation intersubject variability was different when executing a functional movement compared with constrained humeral elevation in the scapular plane. The intersubject CMC values for scapular upward rotation for constrained humeral elevation in the scapular plane were found to be similar to the shelf and overhead tasks (**TABLE 2**). In the constrained trials the scapular plane is defined as 30° to 45° relative to the thorax at a specific humeral elevation of usually 90°, but during elevation the scapula slides and rotates, altering the actual scapular plane position.[32] Studies have found differences in scapular kinematics related to the plane of humeral elevation[25,28] that may lead to higher intersubject variability in the constrained humeral elevation. Based on the observed variability, it appears that functional tasks, such as the overhead or shelf tasks, can be just as useful for evaluating between group differences. While low CMC values for scapular posterior tilting and even lower values for scapular internal rotation are partly due to differing motion patterns, they can also be attributed to large offset differences between subjects due to anatomic variability and small range-of-motion values for these angles.

In the present study subjects performed each task once, to avoid fatigue, thus intrasubject reliability calculations could not be performed. Scapular kinematics have been found to be reliable under constrained protocols in the frontal, scapular, and sagittal planes.[40] To the best of our knowledge, no reliability tests have been reported for scapular kinematics while performing functional shoulder protocols. However, functional movements, such as the ones in the present study, are used more frequently in daily activities than constrained motion.

One of the main issues when using surface sensors methods to measure scapular and humeral kinematics is skin artifact. We have previously reported RMS error for scapular posterior tilt, upward rotation, and external rotation to be 6.2°, 4.5°, and 5°, respectively.[11] This method has been extensively used in our laboratory and has demonstrated good reliability.[41] Ludewig et al[15] found that RMS errors for humeral plane of elevation, elevation, and external rotation were 3.8°, 3.1°, and 7.5°, respectively. For both constrained and functional protocols, the same surface sensors were used, so the error related to skin artifact should be consistent in both protocols. Not randomizing the order between the constrained and functional protocols may have introduced error related to fatigue or sensor slip. To minimize fatigue, subjects had 3 minutes of rest between the constrained trials and the functional testing, which consisted of only 6 tasks, with 4 of them involving less than 90° of arm elevation.

Another reason for the differences between the constrained and functional shoulder movements may be caused by differences in the third humeral rotation, humeral external/internal rotation. McClure et al[25] showed that at 90° of arm elevation while performing full range of humeral external/internal rotation scapular orientation could have changed by up to 15°. In the present study, the third humeral rotation was controlled in the constrained trials but not in the functional testing. The RMS difference for the humeral third rotation, internal/external rotation, was calculated for each functional task and its corresponding interpolated constrained data. The RMS differences were 7° to 14° for the different tasks. Ludewig et al[15] showed RMS error of 7.5° when using surface sensors in comparison to bone pins when measuring humeral external/internal rotation during elevation in the scapular plane; however, the results were based on 1 subject. The motions in the current study were performed in mid range of the humeral internal/external rotation and not at the end range of the motion, which might have decreased the error due to skin motion artifact.

McQuade and Smidt[26] found that differences in shoulder load have an influence on scapular motion. In the constrained trials the elbow was extended during the entire range of motion, as compared to the functional movement, where the elbow was flexed to varying degrees for different tasks. This would have created differences in shoulder torque, which might have influenced muscle activation and coordination levels. During functional testing, the thoracic posture was not controlled (for example, trunk flexion during the reach out task); whereas, in the constrained trials the thorax was restricted, which might have altered scapular position and orientation. It has been shown that different thoracic positions (erect and slouched postures while in seated position) have an influence on scapular kinematics and muscle force output.[7,12]

Humeral elevation angular velocity was controlled in the constrained trials to approximately 40°/s but was not controlled during the different functional tasks, with averaged angular velocities of 30°/s to 120°/s for the different tasks. However, Fayad et al[6] found that there were no significant differences in scapular kinematics at 2 self-selected velocities. If the angular velocities of the functional tasks were controlled to match the constrained trials averaged angular velocity, the functional tasks would have lost their natural pattern and become partially constrained. In the present study we chose to constrain the motion by using verbal feedback to constrain the elbow motion and trunk motion. It may be that if less or more constrained methods were used to quantify scapular kinematics scapular angle differences would have been different.

Finally, in the present study, we used a correction equation previously developed in our lab to minimize errors due to skin artifact using the scapula tracker.[11] This equation was developed based on different anatomical landmarks and a different magnetic tracking device, which might have influenced the scapular orientation angles reported in this study. However, our goal was to determine the differences between constrained and functional shoulder movements and not the absolute values of the different scapular rotations. Even if the application of the correction equation caused an error in scapular angles, this would be a systematic error for both the functional and constrained shoulder movements that would not significantly influence the magnitude of the differences between constrained and functional movements.

CONCLUSION

The findings of this study showed that differences were evident in scapular behavior between constrained and functional motion. The largest differences were observed in scapular upward rotations. Tasks that involved small humeral elevation and/or involved trunk flexion had higher angle difference relative to the task's range of motion. Intersubject variability in constrained humeral elevation in the scapular plane was similar to the variability in overhead and shelf functional tasks. This leads to the first conclusion that investigators should use caution when comparing and generalizing scapular kinematic data collected from constrained humeral movements and applying it to functional humeral movements. Second, based on the results from the current study, it seems that it is not always necessary to use constrained humeral elevation in the scapular plane to measure scapular behavior, because the intersubject variability is the same or in some cases larger than for overhead functional tasks. ◉

KEY POINTS

FINDINGS: When comparing scapular position between constrained and functional shoulder motion, differences were observed for all scapular rotations. Also, similar scapular rotation variability was observed for overhead tasks and constrained arm elevation in the scapular plane.

IMPLICATION: The results provide additional justification for the use of functional tasks to investigate scapular behavior in daily activities. Researchers should be cautious when comparing and generalizing scapular kinematic data collected from constrained humeral movements and applying it to functional humeral movements.

CAUTION: Intrasubject reliability data were not collected in the present study.

REFERENCES

1. Bagg SD, Forrest WJ. A biomechanical analysis of scapular rotation during arm abduction in the scapular plane. *Am J Phys Med Rehabil.* 1988;67:238-245.
2. Borstad JD, Ludewig PM. Comparison of scapular kinematics between elevation and lowering of the arm in the scapular plane. *Clin Biomech (Bristol, Avon).* 2002;17:650-659.
3. Dayanidhi S, Orlin M, Kozin S, Duff S, Karduna A. Scapular kinematics during humeral elevation in adults and children. *Clin Biomech (Bristol, Avon).* 2005;20:600-606. http://dx.doi.org/10.1016/j.clinbiomech.2005.03.002
4. de Groot JH, Brand R. A three-dimensional regression model of the shoulder rhythm. *Clin Biomech (Bristol, Avon).* 2001;16:735-743.
5. Doody SG, Freedman L, Waterland JC. Shoulder movements during abduction in the scapular plane. *Arch Phys Med Rehabil.* 1970;51:595-604.
6. Fayad F, Hoffmann G, Hanneton S, et al. 3-D scapular kinematics during arm elevation: effect of motion velocity. *Clin Biomech (Bristol, Avon).* 2006;21:932-941. http://dx.doi.org/10.1016/j.clinbiomech.2006.04.015
7. Finley MA, Lee RY. Effect of sitting posture on 3-dimensional scapular kinematics measured by skin-mounted electromagnetic tracking sensors. *Arch Phys Med Rehabil.* 2003;84:563-568. http://dx.doi.org/10.1053/apmr.2003.50087
8. Finley MA, McQuade KJ, Rodgers MM. Scapular kinematics during transfers in manual wheelchair users with and without shoulder impingement. *Clin Biomech (Bristol, Avon).* 2005;20:32-40. http://dx.doi.org/10.1016/j.clinbiomech.2004.06.011
9. Inman VT, Saunders JB, Abbott LC. Observations of the function of the shoulder joint. 1944. *Clin Orthop Relat Res.* 1996;3-12.
10. Kadaba MP, Ramakrishnan HK, Wootten ME, Gainey J, Gorton G, Cochran GV. Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait. *J Orthop Res.* 1989;7:849-860. http://dx.doi.org/10.1002/jor.1100070611
11. Karduna AR, McClure PW, Michener LA, Sennett B. Dynamic measurements of three-dimensional scapular kinematics: a validation study. *J Biomech Eng.* 2001;123:184-190.
12. Kebaetse M, McClure P, Pratt NA. Thoracic position effect on shoulder range of motion, strength, and three-dimensional scapular kinematics. *Arch Phys Med Rehabil.* 1999;80:945-950.
13. Lin JJ, Hanten WP, Olson SL, et al. Functional activities characteristics of shoulder complex movements: exploration with a 3-D electromagnetic measurement system. *J Rehabil Res Dev.* 2005;42:199-210.
14. Lin JJ, Hanten WP, Olson SL, et al. Functional activity characteristics of individuals with shoulder dysfunctions. *J Electromyogr Kinesiol.* 2005;15:576-586. http://dx.doi.org/10.1016/j.jelekin.2005.01.006
15. Ludewig PA, Cook TM, Shields RK. Comparison of surface sensor and bone-fixed measurement of humeral motion. *J Appl Biomech.* 2002;18:163-170.
16. Ludewig PM, Cook TM. Alterations in shoulder kinematics and associated muscle activity in people with symptoms of shoulder impingement. *Phys Ther.* 2000;80:276-291.
17. Ludewig PM, Cook TM, Nawoczenski DA. Three-dimensional scapular orientation and muscle activity at selected positions of humeral elevation. *J Orthop Sports Phys Ther.* 1996;24:57-65.
18. Ludewig PM, Reynolds JF. The association of scapular kinematics and glenohumeral joint pathologies. *J Orthop Sports Phys Ther.* 2009;39:90-104. http://dx.doi.org/10.2519/jospt.2009.2808
19. Lukasiewicz AC, McClure P, Michener L, Pratt N, Sennett B. Comparison of 3-dimensional scapular position and orientation between subjects with and without shoulder impingement. *J Orthop Sports Phys Ther.* 1999;29:574-583; discussion 584-576.
20. Mackey AH, Walt SE, Lobb GA, Stott NS. Reliability of upper and lower limb three-dimensional kinematics in children with hemiplegia. *Gait Posture.* 2005;22:1-9. http://dx.doi.org/10.1016/j.gaitpost.2004.06.002
21. Magermans DJ, Chadwick EK, Veeger HE, van der Helm FC. Requirements for upper extremity motions during activities of daily living. *Clin Biomech (Bristol, Avon).* 2005;20:591-599. http://dx.doi.org/10.1016/j.clinbiomech.2005.02.006
22. Matias R, Pascoal AG. The unstable shoulder in arm elevation: a three-dimensional and electromyographic study in subjects with glenohumeral instability. *Clin Biomech (Bristol, Avon).* 2006;21 Suppl 1:S52-58. http://dx.doi.org/10.1016/j.clinbiomech.2005.09.014
23. McClure PW, Bialker J, Neff N, Williams G, Karduna A. Shoulder function and 3-dimensional kinematics in people with shoulder impingement syndrome before and after a 6-week exercise program. *Phys Ther.* 2004;84:832-848.
24. McClure PW, Michener LA, Karduna AR. Shoulder function and 3-dimensional scapular kinematics in people with and without shoulder impingement syndrome. *Phys Ther.* 2006;86:1075-1090.
25. McClure PW, Michener LA, Sennett BJ, Karduna AR. Direct 3-dimensional measurement of scapular kinematics during dynamic movements in vivo. *J Shoulder Elbow Surg.* 2001;10:269-277. http://dx.doi.org/10.1067/mse.2001.112954
26. McQuade KJ, Smidt GL. Dynamic scapulohumeral rhythm: the effects of external resistance during elevation of the arm in the scapular plane. *J Orthop Sports Phys Ther.* 1998;27:125-133.
27. Mell AG, LaScalza S, Guffey P, et al. Effect of rotator cuff pathology on shoulder rhythm. *J Shoulder Elbow Surg.* 2005;14:58S-64S. http://dx.doi.org/10.1016/j.jse.2004.09.018
28. Meskers CG, Vermeulen HM, de Groot JH, van Der Helm FC, Rozing PM. 3D shoulder position measurements using a six-degree-of-freedom electromagnetic tracking device. *Clin Biomech (Bristol, Avon).* 1998;13:280-292.
29. Nawoczenski DA, Clobes SM, Gore SL, et al. Three-dimensional shoulder kinematics during a pressure relief technique and wheelchair transfer. *Arch Phys Med Rehabil.* 2003;84:1293-1300.
30. Neter J, Kutner MH, Nachtsheim CJ, Wasserman W. *Applied Linear Statistical Models.* Chicago, IL: McGraw-Hill/Irwin; 1996.
31. Pascoal AG, van der Helm FF, Pezarat Correia P, Carita I. Effects of different arm external loads on the scapulo-humeral rhythm. *Clin Biomech (Bristol, Avon).* 2000;15 Suppl 1:S21-24.
32. Pearl ML, Jackins S, Lippit SB, Sidle JA, Matsen III FA. Humeroscapular positions in a shoulder range-of-motion examination. *J Shoulder Elbow Surg.* 1992;1:296-305.
33. Poppen NK, Walker PS. Normal and abnormal motion of the shoulder. *J Bone Joint Surg Am.* 1976;58:195-201.
34. Roux L, Hanneton S, Roby-Brami A. Shoulder movements during the initial phase of learning

manual wheelchair propulsion in able-bodied subjects. *Clin Biomech (Bristol, Avon).* 2006;21 Suppl 1:S45-51. http://dx.doi.org/10.1016/j.clinbiomech.2005.09.013
35. Rundquist PJ. Alterations in scapular kinematics in subjects with idiopathic loss of shoulder range of motion. *J Orthop Sports Phys Ther.* 2007;37:19-25. http://dx.doi.org/10.2519/jospt.2007.2121
36. Rundquist PJ, Anderson DD, Guanche CA, Ludewig PM. Shoulder kinematics in subjects with frozen shoulder. *Arch Phys Med Rehabil.* 2003;84:1473-1479.
37. Sainburg RL, Lateiner JE, Latash ML, Bagesteiro LB. Effects of altering initial position on movement direction and extent. *J Neurophysiol.* 2003;89:401-415. http://dx.doi.org/10.1152/jn.00243.2002
38. Steinwender G, Saraph V, Scheiber S, Zwick EB, Uitz C, Hackl K. Intrasubject repeatability of gait analysis data in normal and spastic children. *Clin Biomech (Bristol, Avon).* 2000;15:134-139.
39. Suprak DN, Osternig LR, van Donkelaar P, Karduna AR. Shoulder joint position sense improves with elevation angle in a novel, unconstrained task. *J Orthop Res.* 2006;24:559-568. http://dx.doi.org/10.1002/jor.20095
40. Thigpen CA, Gross MT, Karas SG, Garrett WE, Yu B. The repeatability of scapular rotations across three planes of humeral elevation. *Res Sports Med.* 2005;13:181-198.
41. Tsai NT, McClure PW, Karduna AR. Effects of muscle fatigue on 3-dimensional scapular kinematics. *Arch Phys Med Rehabil.* 2003;84:1000-1005.
42. Veeger HE. The position of the rotation center of the glenohumeral joint. *J Biomech.* 2000;33:1711-1715.
43. Veeger HE, Magermans DJ, Nagels J, Chadwick EK, van der Helm FC. A kinematical analysis of the shoulder after arthroplasty during a hair combing task. *Clin Biomech (Bristol, Avon).* 2006;21 Suppl 1:S39-44. http://dx.doi.org/10.1016/j.clinbiomech.2005.09.012
44. Wang CH, McClure P, Pratt NE, Nobilini R. Stretching and strengthening exercises: their effect on three-dimensional scapular kinematics. *Arch Phys Med Rehabil.* 1999;80:923-929.
45. Westfall PH, Tobias RD, Rom D, Wolfinger RD, Hochberg Y. *Multiple Comparisons and Multiple Tests Using the SAS System.* Cary, NC: SAS Institute, Inc; 1999.
46. Wu G, van der Helm FC, Veeger HE, et al. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion--Part II: shoulder, elbow, wrist and hand. *J Biomech.* 2005;38:981-992.