Direct 3-dimensional measurement of scapular kinematics during dynamic movements in vivo

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The purpose of this study was to describe 3-dimensional scapular motion patterns during dynamic shoulder movements with the use of a direct technique. Direct measurement of active scapular motion was accomplished by insertion of 2 1.6-mm bone pins into the spine of the scapula in 8 healthy volunteers (5 men, 3 women). A small, 3-dimensional motion sensor was rigidly fixed to the scapular pins. Sensors were also attached to the thoracic spine (T3) with tape and to the humerus with a specially designed cuff. During active scapular plane elevation, the scapula upwardly rotated (mean [SD] = 50° [4.8°]), tilted posteriorly around a medial-lateral axis (30° [13.0°]), and externally rotated around a vertical axis (24° [12.8°]). Lowering of the arm resulted in a reversal of these motions in a slightly different pattern. The mean ratio of glenohumeral to scapulothoracic motion was 1.7:1. Normal scapular motion consists of substantial rotations around 3 axes, not simply upward rotation. Understanding normal scapular motion may assist in the identification of abnormal motion associated with various shoulder disorders. (J Shoulder Elbow Surg 2001;10:269-77.)

Proper scapular motion and stability is considered to be crucial to normal function of the shoulder. The scapula must serve as a stable base for glenohumeral function but it also must move through a substantial arc of motion. This motion is required to maintain optimal muscle length-tension relations and glenohumeral joint alignment during elevation of the arm. Because of these demands, abnormal scapular motion has been found to be associated with pathologies such as the impingement syndrome and glenohumeral instability.[13,17,24]

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Scapular motion has been studied by various methods. The classic work of Inman et al[7] in 1944 used 2-dimensional analysis of radiographs to document scapular position, as did many subsequent investigators.[5,19] Inman et al found an overall 2:1 relation between glenohumeral elevation and scapular upward rotation, which has remained the classic description of the so-called scapulohumeral rhythm. Other authors have also measured scapular motion with simple 2-dimensional goniometric methods.[4,25] Most previous 2-dimensional studies have focused on upward rotation of the scapula during scapular plane elevation. However, 2-dimensional methods fail to account for "out-of-plane" motions, which may produce significant errors and also may fail to capture the complexity of the movement.[3]

More recent efforts have begun to identify other components of a more complex, 3-dimensional scapular motion pattern with the use of 3-dimensional radiographic, digitizing, and electromagnetic-based measurement systems.[6,11,12,14,16,18,22] The scapula has been particularly difficult to track during dynamic shoulder function. This is because digitizing and radiographic techniques require static positioning and dynamic tracking with surface markers. Use of surface markers is made difficult because of the scapula's broad, flat shape, its substantial soft-tissue covering, and the significant subcutaneous motion.

The purpose of this article was to describe the direct, 3-dimensional motion of the scapula during dynamic arm motions performed in vivo under various conditions. We used a 3-dimensional electromagnetic-based system and attached a motion sensor directly to the scapula with bone pins drilled into the spine of the scapula with the patient under local anesthesia. This work is part of a larger study directed at quantifying the error associated with a noninvasive measurement technique.[9]

MATERIALS AND METHODS

Subjects

Eight healthy volunteers (5 men, 3 women) with a mean age of 32.6 years (range 27 to 37 years) without shoulder pathologies were recruited for this study. The mean body mass index was 25.2 kg/m^2 (range 19.1 to 35.2 kg/m^2). All subjects were right-hand dominant, and the left shoul-

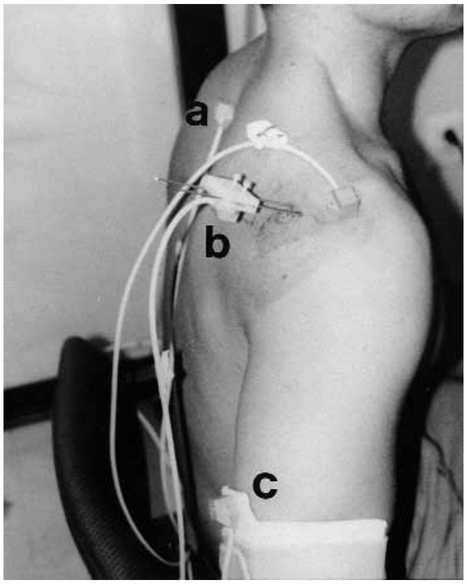


Figure 1 Subject with motion sensors attached: thoracic sensor *(a)*, scapular sensor attached to bone pins (via plastic guide) inserted into the scapula *(b)*, and humeral sensor mounted on custom cuff applied to the distal humerus *(c)*. The sensor mounted on the acromion (not labeled) was used for data related to another study.

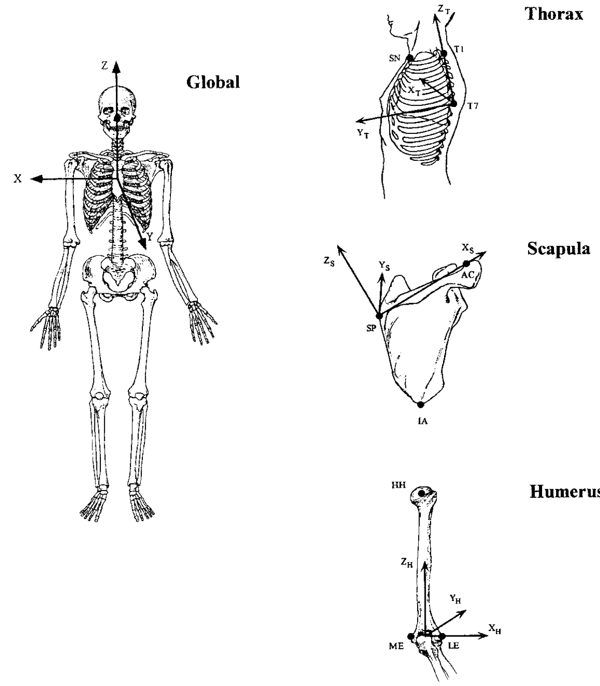


Figure 2 Anatomic landmarks used for digitization and coordinate axes for each segment. Global*: X,* lateral; *Y,* anterior; *Z,* superior. Thorax: *T1,* first thoracic vertebrae; *T7,* seventh thoracic vertebrae; *SN,* sternal notch; Z_T, vector connecting T7 to T1; X_T, vector perpendicular to plane T1-T7-SN; Y_T, cross product of Z_T and X_T. Scapula: *AC,* acromioclavicular joint; *SP,* root of scapular spine; *IA,* inferior angle; X_S, vector connecting SP to AC; Y_S, vector perpendicular to plane AC-SP-IA; Z_S, cross product of X_S and Y_S. Humerus: *HH,* center of humeral head; *LE,* lateral epicondyle; *ME,* medial epicondyle; Z_H, vector connecting mid point of ME and LE to HH; Y_H, vector perpendicular to plane ME-LE-HH; X_H, cross product of Y_H and Z_H.

der was tested in 7 of the 8 subjects. Approval was obtained from the internal review board of MCP-Hahnemann University, and all subjects read and signed a consent form before participation in the study.

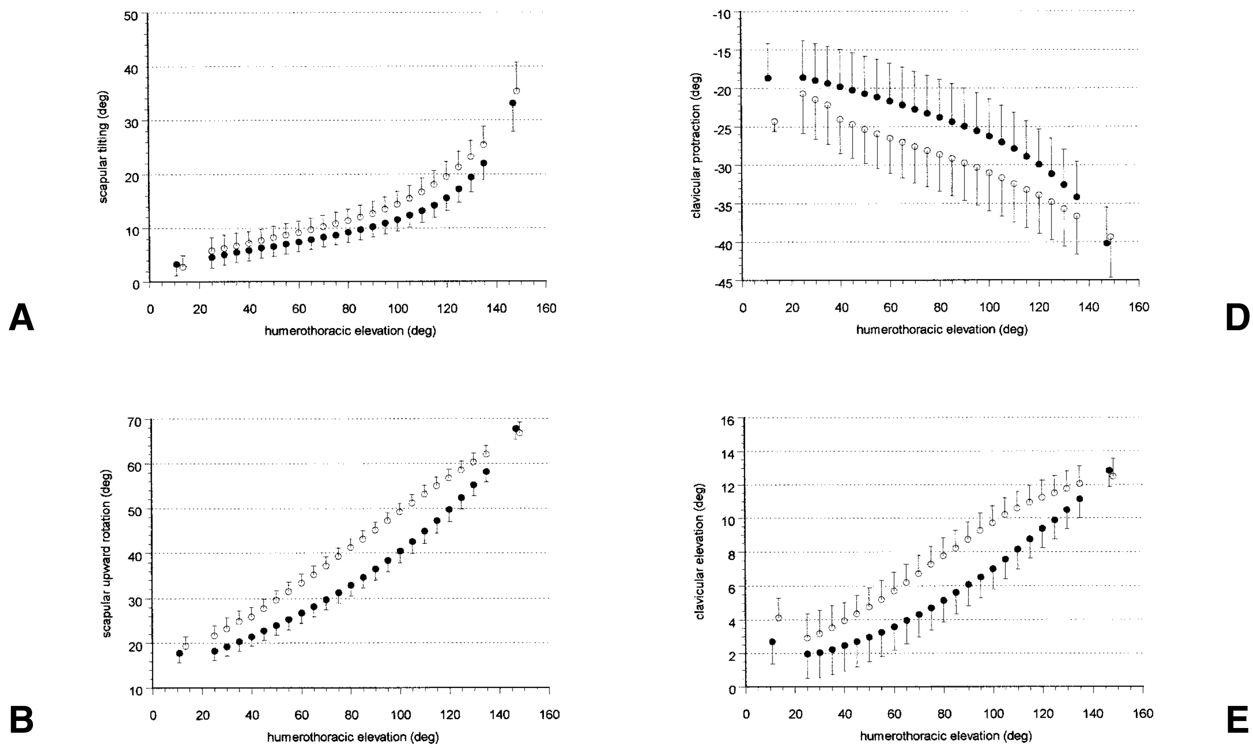
Instrumentation

Rotational motion was measured with an electromagnetic tracking device (Polhemus 3Space Fastrak, Colchester, Vt). The manufacturer has reported an accuracy of 0.8 mm and 0.15° for this device, and we have verified this accuracy under controlled laboratory conditions. A global coordinate system was established by mounting the Polhemus transmitter on a rigid plastic base. The transmitter was aligned with the cardinal planes of the body by using a small jig that aligned a subject's heels along a line parallel with the transmitter (G_S axis), and subjects were instructed to look straight ahead throughout testing. To ensure that the transmitter was level, the orientation was adjusted with visual feedback from a bubble level. Receivers were mounted on the thorax, humerus, and scapula. The thorax receiver was placed at the level of the third thoracic spinous process (T3) with double-sided tape. The humeral receiver was mounted on a molded cuff strapped to the distal humerus. The scapular receiver was fixed to the scapula with pins inserted under sterile conditions by an orthopaedic surgeon . A small region on the lateral scapular spine was cleaned and anesthetized with lidocaine. Two 1.6-mm bone pins then were drilled into the spine of the scapula transcortically, 1 inch apart, with the use of a plastic alignment jig to keep them parallel. After determining that the pins were secure in the bone, they were fixed to the alignment jig with setscrews. The scapula receiver was then secured to this jig for ideal coupling between scapula and receiver (Figure 1).

Kinematics

The arbitrary axes defined by the Polhemus were converted to anatomically appropriate embedded axes, which were derived from digitized bony landmarks (Figure 2). An embedded axis system is a means of achieving an anatomically meaningful axis system within each specific bone being studied. The bony landmarks chosen to define each bone are similar to those in previous studies.[12,16] All bony landmarks were surface points and thus could be located with a digitizer connected to the Polhemus, except for the center of the humeral head. This was defined as the point on the humerus that moved the least when the humerus was moved through short arcs (<45°) of midrange glenohumeral motion and was calculated with use of a least-squares algorithm.[20]

Motion of the humerus with respect to the thorax was represented with a standard Euler angle sequence 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.[1,8] Rota-



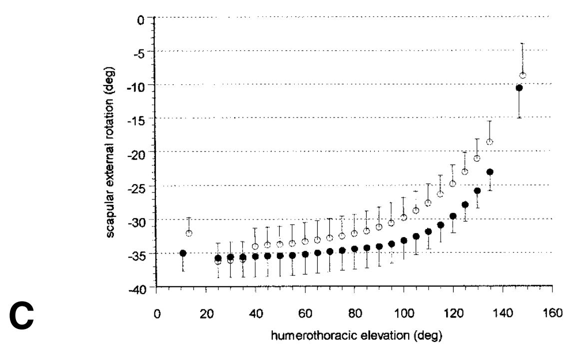


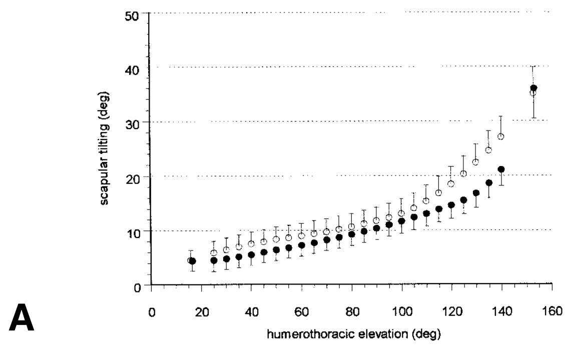
Figure 3 Scapular and clavicular rotations during active scapular plane abduction (mean ± SEM). **A,** Scapular posterior tilting; **B,** scapular upward rotation; **C,** scapular external rotation; **D,** clavicular plane rotation; **E,** clavicular elevation. Because subjects varied in total range of humerothoracic motion, the minimum and maximum points represent the average of the 8 subjects. ●, Raising the arm; ○, lowering the arm; *deg,* degrees.

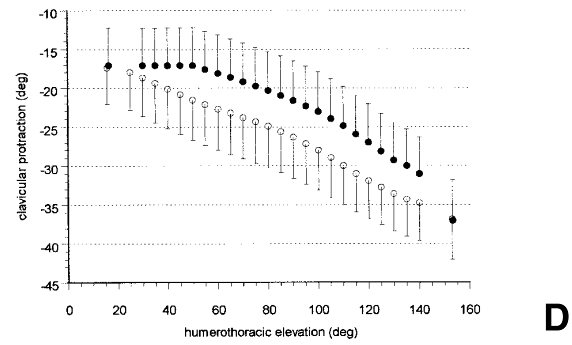
tional motion of the scapula with respect to the thorax was described on the basis of a Euler angle sequence of external/internal rotation (Z_S axis), upward/downward rotation (Y_S axis), and posterior/anterior tilting (X_S axis).[21,22]

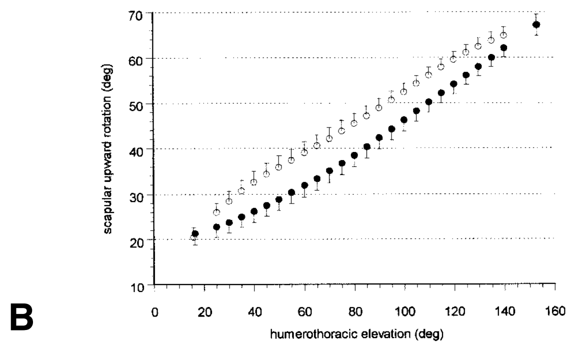
The position of the scapula was represented by the rotational motion of the clavicle. The scapula is connected to the thorax by means of the sternoclavicular and acromioclavicular joints, both of which are assumed to exhibit ball-and-socket kinematics, which implies that only rotation and no translation occurs at these joints. Consequently, the orientation of the scapula with respect to the thorax has 3 degrees of freedom and can be represented by the 3 Euler angles described above. However, because of the rigidity of the clavicle, which spans these 2 joints, the distance between them is kept constant. Therefore, the position of the scapula is restricted to only 2 degrees of freedom and can be represented by the rotational motion of the clavicle: retraction/protraction and elevation. This is equivalent to describing the position of a point on the Earth with the use of 2 angles: longitude and latitude. Clavicular motion was not monitored directly, but rather, clavicular angles were derived from the location of the sternal notch and the acromioclavicular joint, which were tracked with the thoracic and scapular receivers, respectively.

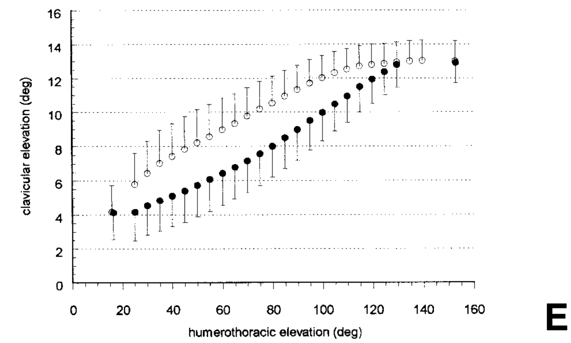
Experimental protocol

After the digitization process, the raw data from the 3 receivers were converted to anatomically defined rotations that could be displayed in real time in LabView (National Instruments, Austin, Tex). Subjects stood with their eyes fixed forward, feet at a comfortable width apart, and heels against a rigid support. A total of 3 active motions were studied: (1) scapular plane elevation: elevation of the humerus in the scapular plane (40° anterior to the frontal









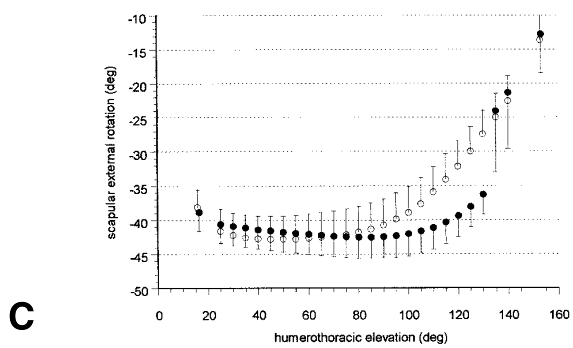
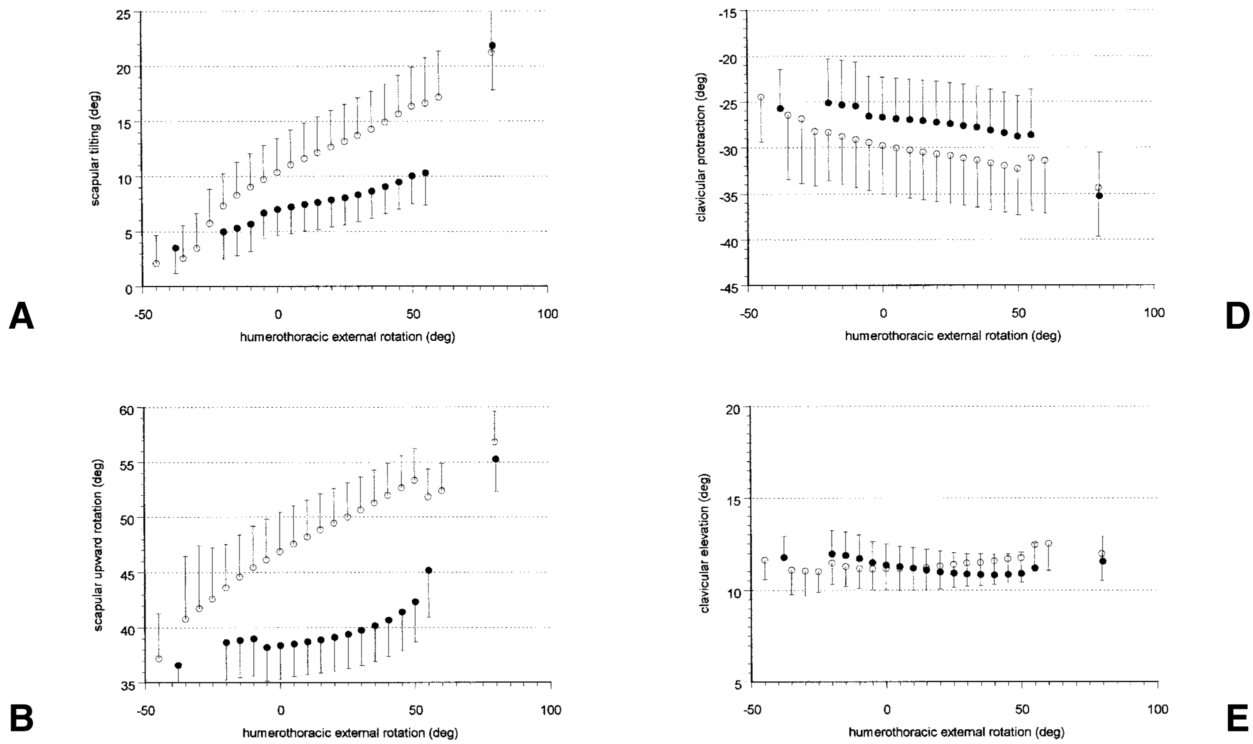


Figure 4 Scapular and clavicular rotations during active sagittal plane flexion (mean ± SEM). **A,** Scapular posterior tilting; **B,** scapular upward rotation; **C,** scapular external rotation; **D,** clavicular plane rotation; **E,** clavicular elevation. Because subjects varied in total range of humerothoracic motion, the minimum and maximum points represent the average of the 8 subjects. ●, Raising the arm; ○, lowering the arm; *deg,* degrees.

plane) with the elbow in full extension and thumb pointing up, (2) flexion: elevation of the humerus in the sagittal plane (90° anterior to the frontal plane) with the elbow in full extension and the thumb pointing up, and (3) internal-to-external rotation with the arm elevated 90° in the frontal plane and the elbow flexed to 90°. The starting position for scapular plane elevation and flexion was with the arm by the side with the palm against the thigh.

Subjects were asked to refrain from watching their arms or the computer screen during the motion. For scapular plane elevation and flexion, a series of practice trials were performed in which the investigator monitored the plane of elevation on the computer and provided the subject with verbal feedback. Once the subject could accurately reproduce the correct motion (correct plane of elevation maintained within ±5°), data collection began. For internal/external rotation, the investigator monitored arm position so that the 90°-elevation position was maintained.

For each motion, subjects moved their arm maximally through the range to a count of 3 and then returned along the same path, with data collected continuously at a rate of approximately 10 Hz. This procedure was repeated for 3 consecutive trials. For each trial, the minimum and maximum elevation points were calculated, and the rest of the data were linearly interpolated in 5° increments of humerothoracic motion. These data were averaged over the 3 trials. For each arm motion we assessed separately the phases in which the humeral angle was increasing (elevation or external rotation) and decreasing (lowering or internal rotation). To describe motion for the group, the interpolated data from all subjects were pooled, and a single curve for each particular arm motion and scapular or clavicular rotation was plotted.



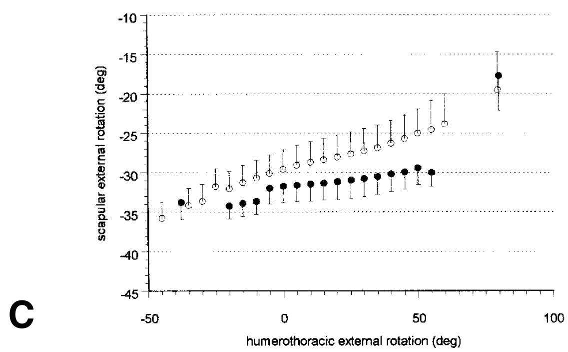


Figure 5 Scapular and clavicular rotations during humeral external/internal rotation with the arm abducted 90° in the coronal plane (mean ± SEM). **A,** Scapular posterior tilting; **B,** scapular upward rotation; **C,** scapular external rotation; **D,** clavicular plane rotation; **E,** clavicular elevation. Because subjects varied in total range of humerothoracic motion, the minimum and maximum points represent the average of the 8 subjects. ●, Moving from internal to external rotation; ○, moving from external to internal rotation; *deg,* degrees.

RESULTS

During scapular plane elevation of the arm, there was a consistent pattern of scapular upward rotation, posterior tilting, and external rotation along with clavicular elevation and retraction (Figure 3). Upward rotation of the scapula and clavicular rotation occurred approximately linearly throughout humeral elevation, especially beyond 50° of elevation. Posterior tilting and external rotation motions were nonlinear, with the majority of these motions not occurring until after 90° of arm elevation. The results of sagittal plane elevation (flexion) are shown in Figure 4 and do not differ substantially from the motions observed during scapular plane elevation.

For external/internal humeral rotation, relatively little scapular rotation occurred except at the end-range of external rotation (Figure 5). As full humeral external rotation was achieved, the scapula upwardly rotated, tilted posteriorly, and externally rotated while the clavicle retracted.

Although the path of motion during the lowering phase of the activity was slightly different in some cases, mean scapular orientation during lowering was typically within 5° compared with the elevation phase of the activity. For both scapular plane elevation and flexion, the greatest differences between the two phases occurred in scapular upward rotation during the mid range between approximately 60° and 120°. During humeral external/internal rotation, the greatest differences between the phases seemed to occur in scapular

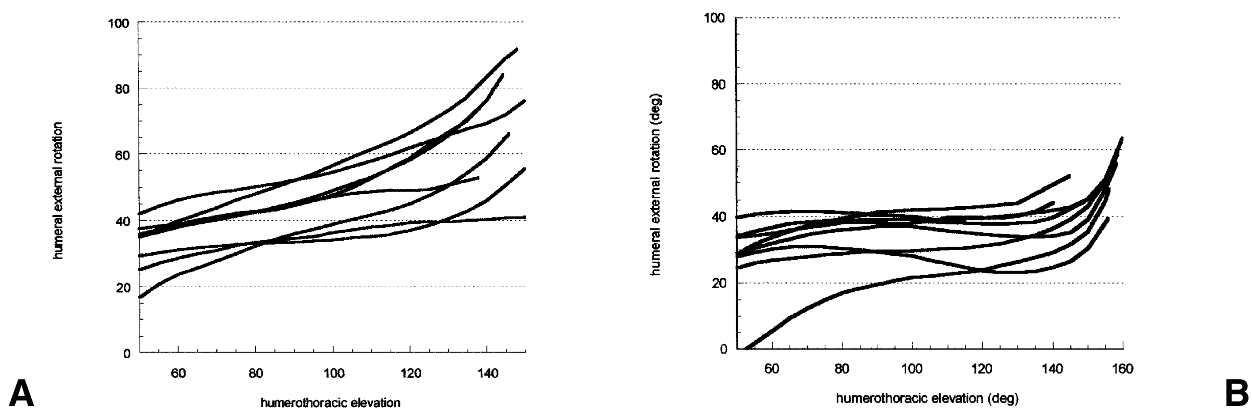


Figure 6 Humeral external rotation relative to the thorax during arm elevation. **A,** Scapular plane elevation; **B,** sagittal plane flexion. *deg,* Degrees.

tilting and upward rotation between 30° and 60° of humeral external rotation.

The amount of humeral external rotation during elevation was not constrained and could have influenced scapular motion. This motion is depicted for all subjects in Figure 6. These graphs show that the humerus externally rotated during scapular plane elevation sooner and to a greater extent than during flexion.

DISCUSSION

Comparing data across studies is difficult because of several important methodologic differences. These differences include the specific arm motion studied (ie, the plane of elevation and the specific range of motion studied), static versus dynamic motion, trunk position and the degree of stabilization, the type and number of subjects, and differing measurement techniques. Aside from the different instruments used to obtain measurements, many other factors affect the results when scapular motion is studied. These include the choice of bony landmarks used to create local coordinate frames, the method used to calculate angles and describe motion (ie, planar projections, Euler angles, helical axis), choice of a fixed reference frame (ie, various thoracic definitions or a global system that uses pure vertical and horizontal references), and the specific methods used to reduce and present the data, such as whether the resting position is taken as zero or is given a value on the basis of a defined anatomic zero position. Also, various ratios have been used to characterize motion and scapulohumeral rhythm. Given these differences, it is not surprising that variation exists in the literature relating to scapular kinematics.

Despite the above concerns, we attempted to compare our findings with those of previous studies (See Table).* Scapular upward rotation has been the most extensively studied motion, and previous authors report values above and below those found in this study. A common method of assessing upward rotation has been to characterize the ratio of glenohumeral motion to scapulothoracic upward rotation motion (GH/ST). The GH/ST for the pooled data in our study was 2.0 for flexion and 1.7 for scapular plane elevation. Various GH/ST ratios have been obtained previously by other authors ranging from 1.25[19] to 3.2[12] under similar conditions. This ratio can be affected by the method used to measure humeral motion. Most studies seem to assume a 0° starting position of the humerus, whereas some others actually measure the rest position, which is typically greater than zero. If we assume a 0° starting position for humeral elevation with our data, the GH/ST ratios become 2.3 and 1.9 for flexion and scapular plane abduction, respectively.

The relation between scapular upward rotation and humeral elevation has been generally acknowledged to be nonlinear. To characterize this relation, we performed both linear and polynomial curve fits on the mean data for the ascending phase of scapular plane abduction, as shown in Figure 7. The R^2 value was 0.957 for the linear fit, which would suggest a strong linear relation. However, visual inspection of a linear-curve fit reveals substantial error at the beginning and end of the motion, as is shown in Figure 7. During the first 30° of humerothoracic elevation, the scapula moves very little; whereas at the extreme of elevation, the rate of scapular upward rotation increases compared with the middle range of elevation. The R^2 value for a third order polynomial fit (Figure 7) was 0.999, suggesting a nonlinear relation. Interestingly, the lowering phase demonstrated a much more linear relation (R^2 = 0.997). The significance of this difference is unclear; however, we speculate that greater eccentric neuromuscular control may be exerted on the scapula during the lowering phase of elevation and may be responsible for the slightly different pattern.

Posterior tilting motion has been a less recognized

*References 2, 4, 7, 8, 11, 12, 16, 19, 22.

Table Scapular rotations measured by various authors

Author	Method	Range of arm motion	Mean scapular motion
Inman et al, 1944[7]* (estimated from graphs)	2D radiographs	Flexion 30°-150°	50° Upward rotation 25° Clavicle elevation 30° Clavicle posterior rotation
		FP abd 30°-150°	40° Upward rotation 30° Clavicle elevation 30° Clavicle posterior rotation
Doody et al, 1970[4]*	2D goniometry	SP abd 5°-176°	59° Upward rotation
Poppen and Walker, 1976[19] (estimated from regression equation)†	2D radiographs	SP abd 0°-150°	54° Upward rotation 40° Posterior tilt ("twisting")
Kondo et al, 1984[11]*	3D double radiograph	SP abd 0°-max	60° Upward rotation 24° Posterior tilt 8° Int rotation ("medial tilt")
Bagg and Forrest, 1988[2]†	2D photographic	SP abd 0°-168°	64° Upward rotation
Johnson et al, 1993[8] (mean of 2 testers)*	3D electromagnetic digitizer (static)	FP abd 0°-120°	32° Upward rotation 9° Posterior tilt‡ 6° Int rotation ("protaction")
McQuade et al, 1995[15]	3D electromagnetic digitizer (static)	SP abd 0°-135°	32° Upward rotation 31° Posterior tilt 67° Int rotation§
van der Helm and Pronk, 1995[22] (estimated from graphs)*	3D electromechanical digitizer (static)	Flexion 0°-180°	60° Upward rotation 30° Posterior tilt –25° Int rotation ("retraction") –22° Clavicle protraction 10° Clavicle elevation
		FP abd 0°-180°	60° Upward rotation 30° Posterior tilt –25° Int rotation ("retraction") –22° Clavicle protraction 10° Clavicle elevation
Ludewig et al, 1996[12]*	3D electromechanical digitizer (static)	SP abd 0°-140°	34° Upward rotation 15° Posterior tilt –13° Int rotation
Meskers et al, 1998[16] (values estimated from graphs)*	3D electromagnetic digitizer (quasi-static)	Flexion 0°-150°	58° Upward rotation 24° Posterior tilt‡ 0° Int rotation ("protraction")
		FP abd 0°-150°	60° Upward rotation 13° Posterior tilt‡ 3° Int rotation ("protraction")
Current study (McClure et al)*	3D electromagnetic continuous tracking	Flexion 16°-153°	46° Upward rotation 31° Posterior tilt –26° Int rotation –20° Clavicle protraction 9° Clavicle elevation
		SP abd 11°-147°	50° Upward rotation 30° Posterior tilt –24° Int rotation –21° Clavicle protraction 10° Clavicle elevation

2D, Two-dimensional; *FP abd,* frontal plane abduction; *SP abd,* scapular plane abduction; *3D*, 3-dimensional; *max*, maximum; *int*, internal.
*Values represent total excursion = maximal elevation – rest position.
†Uncertain whether these values represent total excursion or absolute position at maximal elevation.
‡Uncertain whether these values represent posterior or anterior tilting.
§Uncertain whether these values represent internal or external rotation.

aspect of scapular motion during humeral elevation. As shown in the Table, there is wide disparity in the literature as to the amount of tilting that occurs. Unfortunately, some previous studies have not clearly identified the direction of tilting,[8,16] which makes comparison more difficult. The motion pattern was clearly nonlinear, and the majority of tilting motion occurred beyond 90° of elevation, with a very sharp increase at end range. As evidenced by the small standard errors, this motion was quite consistent among the 8 subjects. The presence of posterior tilting may be important functionally to allow for clearance of the humeral head and the rotator cuff tendons under the anterior aspect of the acromion during elevation. In previous work, we iden-

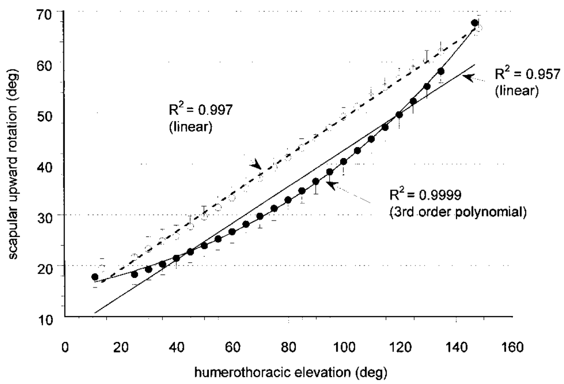


Figure 7 Scapular upward rotation during humeral elevation in the scapular plane. Raising the arm is best represented by the third-order polynomial curve fit, which demonstrates the nonlinear aspect of the relation. Lowering the arm is represented well by a linear fit. ●, Raising the arm; ○, lowering the arm; *deg,* degrees.

tified this motion as a potentially important discriminator between asymptomatic subjects and subjects with impingement syndrome.[13] Subjects with impingement had approximately 10° less posterior tilting compared with asymptomatic subjects.

We found substantially more scapular external rotation during humeral elevation than has been reported previously.[8,11,12,16,22] Similar to the results of posterior tilting, the motion pattern was obviously nonlinear, with the majority of motion occurring beyond 90° elevation and increasing most dramatically at end range. Interestingly, some authors report internal rotation (sometimes termed *protraction*) during elevation, as opposed to our consistent finding of external rotation.[8,11,16] This may represent an inherent problem in palpation-based tracking techniques in which bony landmarks must be followed with a locating device. The functional significance of scapular external rotation motion is unclear. We speculate that external rotation of the scapula may lessen the requirement for glenohumeral external rotation as the arm is fully elevated. If this scapular motion is lacking, it is possible that greater motion demands would be placed on the glenohumeral joint, which could lead to capsular laxity and anterior instability. This motion may also be influenced by the contour of the ribs.

Rotations of the clavicle in 2 different planes (clavicular plane and clavicular elevation) were chosen to describe the position of the scapula during motion because the scapula is constrained by the clavicle. During humeral elevation, the clavicle retracted approximately 20°, indicating posterior movement of the scapula. This motion was greatest from 130° to 150° of humeral elevation, and it did not really begin until approximately 25° of scapular plane elevation and about 50° of flexion. The clavicle elevated a total of approximately 10° during humeral elevation, indicating superior movement of the scapula. We did not track the clavicle directly with bone pins. Inman et al[7] reported approximately 30° of clavicular elevation during humeral elevation and stated that most of the motion occurred by 90° of humeral elevation. It is unclear what method they used to measure clavicular elevation, though it appears radiographs were used. They did insert pins directly in the clavicle of a subject to assess clavicular rotation about its long axis and found approximately 40° of posterior rotation, which occurred mostly after 90° of humeral elevation, yielding a nonlinear curve. We were unable to measure clavicular rotation about its long axis; however, it seems likely that posterior tilting of the scapula may be related to this motion. As the coracoclavicular ligaments become tightened, the clavicle rotates posteriorly, which is probably coupled with posterior scapular tilting.

External and internal rotation of the humerus with the arm abducted 90° in the frontal plane also produced substantial scapular motion. As the humerus approached the extreme of external rotation, the scapula underwent rather abrupt posterior tilting, upward rotation, and external rotation. However, relatively limited scapular motion occurred in the mid ranges of rotation. Although attempts were made to maintain the humerus in 90° abduction, humeral elevation varied between 75° to 95° during the test movements. Humeral external rotation was associated with greater humeral elevation, which may have influenced scapular motion. The scapular motions appear to be important in attaining the end-range positions of humeral rotation. A lack of scapular motion may produce greater stress on the glenohumeral joint capsule and potentially lead to overstretching and laxity.

To our knowledge, only one other study has directly measured scapular motion 3-dimensionally during continuous motion: Koh and colleagues[10] inserted pins in both the scapula and humerus in 3 subjects and tracked the motion during humeral elevation in 3 different planes with the use of a video-based system. Their results are somewhat difficult to interpret and compare with previous work because they present the data with helical axis parameters. Their principal finding was that the scapula rotated primarily around an axis perpendicular to the plane of the scapula.

The precise mechanisms controlling scapular motion are not well understood. Certainly, muscle action is partially responsible for scapular control, and muscle fatigue[15] as well as shoulder strengthening have both been shown to alter the GH/ST ratio.[23] Passive mechanisms may also control scapular motion, such as capsular tightness or laxity, and tension in the coracoclavicular ligaments. Both posterior tilting and external rotation of the scapula increased dramatically as the arm was raised above 90°. It may be that as the glenohumeral joint reaches its limits of motion, the capsular tension generated may pull the scapula along as the arm elevates.

Knowledge of normal scapular motion and the factors that control it could serve as the basis for understanding several pathologies thought to be related to abnormal scapular control, such as impingement syndrome and glenohumeral instability.[13,24] If active muscle control is important, this would support specific rehabilitative exercises designed to strengthen muscles and improve motor control. If passive mechanisms provided by capsular and ligamentous support prove to be important, injuries and interventions designed to alter these factors could be better understood. Our future work will be directed at elucidating the basic mechanisms controlling scapular motion and studying the effects of various pathologies and treatment methods.

Because of the invasive nature of this study, we used a relatively small sample of young, asymptomatic adults, most of whom preferred to have their nondominant, left shoulder girdle tested. Therefore caution must be used in extrapolating these findings to a broader population. No subject complained of pain during the experiment, and the instrumentation was very lightweight and unobtrusive. However, it is possible that the pins and instrumentation may have affected the motion in some way. Also, the motions tested were performed at relatively slow speeds (approximately 30° to 50° per second) in a controlled manner, and functional tasks performed at high velocities may produce different motion patterns.

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