J Shoulder Elbow Surg (2009) 18, 960-967

ELSEVIER

JOURNAL OF
SHOULDER AND
ELBOW
SURGERY

www.elsevier.com/locate/ymse

In vivo assessment of scapulohumeral rhythm during unconstrained overhead reaching in asymptomatic subjects

Jonathan P. Braman, MD[a,*], Sean C. Engel, MD[a], Robert F. LaPrade, MD, PhD[a], Paula M. Ludewig, PT, PhD[b]

[a]*Department of Orthopaedic Surgery, University of Minnesota, Minneapolis, MN*
[b]*Department of Physical Medicine and Rehabilitation, University of Minnesota, Minneapolis, MN*

Background: The contribution of scapulothoracic and glenohumeral motion to overall shoulder motion remains difficult to determine. We sought to determine the exact ratio between these two motion components in order to better understand overall shoulder kinematics in asymptomatic individuals in unconstrained reaching.
Materials and methods: This study assessed shoulder motion using bone-fixed sensors to quantify scapulohumeral motion during unconstrained raising and lowering of the arm. Electromagnetic tracking devices rigidly fixed to bone pins recorded active scapular and humeral motion.
Results: We found a significant difference in the ratio of glenohumeral elevation to scapular upward rotation during arm raising (2.3) and lowering (2.7). Each degree of glenohumeral elevation yielded scapular upward rotation of 0.43° (raising) compared with downward rotation of 0.37° (lowering), across the motion arc. Until 125° of glenohumeral elevation, the scapula internally rotated and then externally rotated with further elevation. Scapular upward rotation and posterior tilting progressively increased until maximal elevation. Scapulohumeral rhythm was greatest in the first increment of raising the arm and higher overall when lowering the arm.
Discussion: Understanding these data allows improved evaluation of potential motion abnormalities in patients with shoulder pathology and may improve treatment for restoration of normal shoulder motion.

Keywords: Scapulohumeral rhythm; shoulder biomechanics; glenohumeral; scapular motion

Scapulohumeral rhythm is the relationship between elevation at the glenohumeral joint and scapular upward rotation. To fully understand the spectrum of shoulder problems, it is important to recognize the contribution of scapulothoracic motion to overall shoulder motion. When this relationship is altered, it leads to shoulder dysfunction. The current emphasis on core strengthening as a method of improving shoulder pain also implies a contribution from the scapulothoracic articulation.[11]

New technologies have allowed for 3-dimensional (3D) assessment of scapular rhythm during active motion. This enables more complete analysis of scapular motion, because the scapula undergoes angular changes with

*Reprint requests: Jonathan P. Braman, MD, Department of Orthopaedic Surgery, University of Minnesota, 2450 Riverside Ave, R200, Minneapolis, MN 55454.

E-mail address: brama011@umn.edu (J.P. Braman).

1058-2746/2009/$36.00 - see front matter © 2009 Journal of Shoulder and Elbow Surgery Board of Trustees.
doi:10.1016/j.jse.2009.02.001

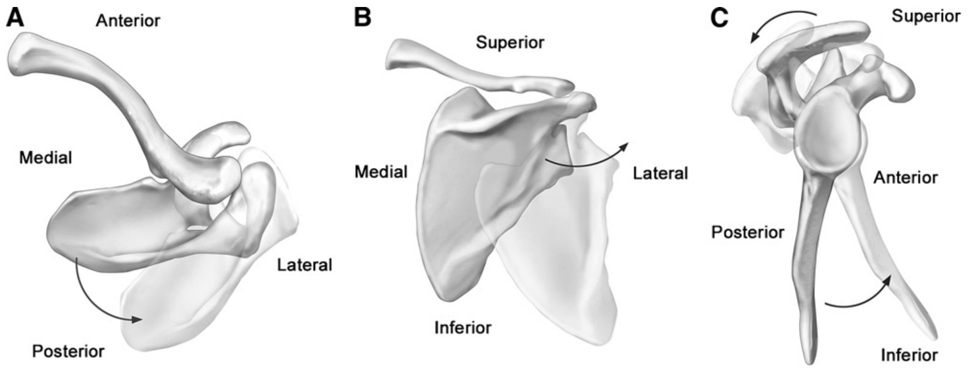

Figure 1 **(A)** Scapular internal and external rotation: (superior view right shoulder) Ghosted image represents increased internal rotation. Please note: with increasing internal rotation, the glenoid articular surface internally rotates. **(B)** Scapular upward rotation (posterior view right shoulder) Ghosted image represents increased upward rotation. Please note: with increased upward rotation, the glenoid articular surface upwardly rotates. **(C)** Scapular tilting (lateral view right shoulder) Ghosted image represents increased posterior tilting. Please note: with increased posterior tilting, the glenoid rotates posteriorly. Reprinted with permission from The Journal of Bone and Joint Surgery, Inc. Motion of the Shoulder Complex During Multiplanar Humeral Elevation. J Bone Joint Surg Am 2009;91:378.

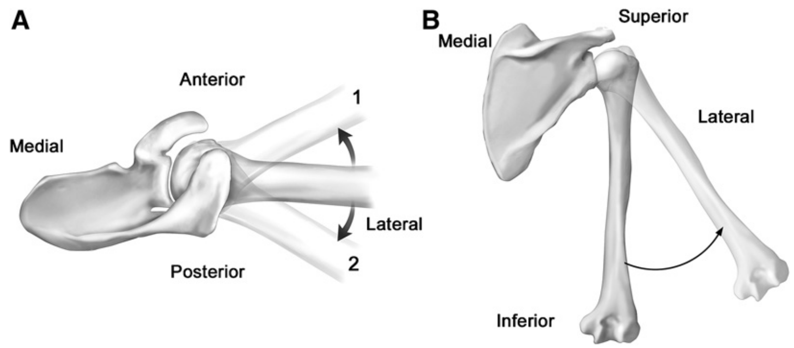

Figure 2 **(A)** Plane of elevation (superior view right shoulder) Ghosted images represent *(1)* anterior and *(2)* posterior to the plane of the scapula. **(B)** Glenohumeral elevation angle (posterior view right shoulder) Ghosted image represents increased glenohumeral elevation. Reprinted with permission from The Journal of Bone and Joint Surgery, Inc. Motion of the Shoulder Complex During Multiplanar Humeral Elevation. J Bone Joint Surg Am 2009;91:378.

humeral motion in the axial, coronal, and sagittal planes. The description of scapulothoracic and glenohumeral motion beyond the components of scapular upward rotation and glenohumeral elevation can now include scapular internal/external rotation and anterior/posterior tilting, as well as plane of glenohumeral elevation and glenohumeral axial rotation (Figures 1 and 2). Finally, reporting of scapular upward/downward rotation using 3D methods is not subject to projection error.

Prior 3D studies of shoulder motion have made use of skin sensors,[12,19,20] palpation methods,[3,17,25] or hybrid techniques.[1,6,18] Earlier studies using roentgenograms have imaged the shoulder in positions throughout the range of motion in the scapular plane.[5,23] These studies, however, are limited by their static nature. In addition, the goniometric study by Doody et al[4] and the roentgenographic study by Freedman et al[5] found that the scapulohumeral rhythm was variable throughout the arc of motion. The invasiveness of bone pins has limited their use; however, substantive reported errors in measurements associated with skin sensors, particularly at higher angles of humeral elevation, limit the precision of surface sensor techniques.[9,15] Bone-fixed tracking is the current gold standard for precise shoulder motion measurement.[6,7,10,16,22]

Past studies have, for purposes of consistency and ease of measurement, limited the measurement of humeral elevation to controlled planes.[4,5,8,13,18,19,23] Also, since Inman et al[8] reported an overall constant scapulohumeral rhythm of 2:1 during humeral elevation in the sagittal (flexion) and coronal (abduction) planes, this ratio has been widely accepted despite numerous subsequent studies[3-5,18,19] that produced different results in different planes. The Inman study[8] is still the landmark study for description of shoulder motion, but it is unclear if there was more than one participant and how the data were collected. As a result, it is difficult to imagine that similar data published today would be so well received.

Newer studies[3-5,18,19] have provided improved description of samples tested and measurement methods, as well as values for the rhythm during increments of overall motion.

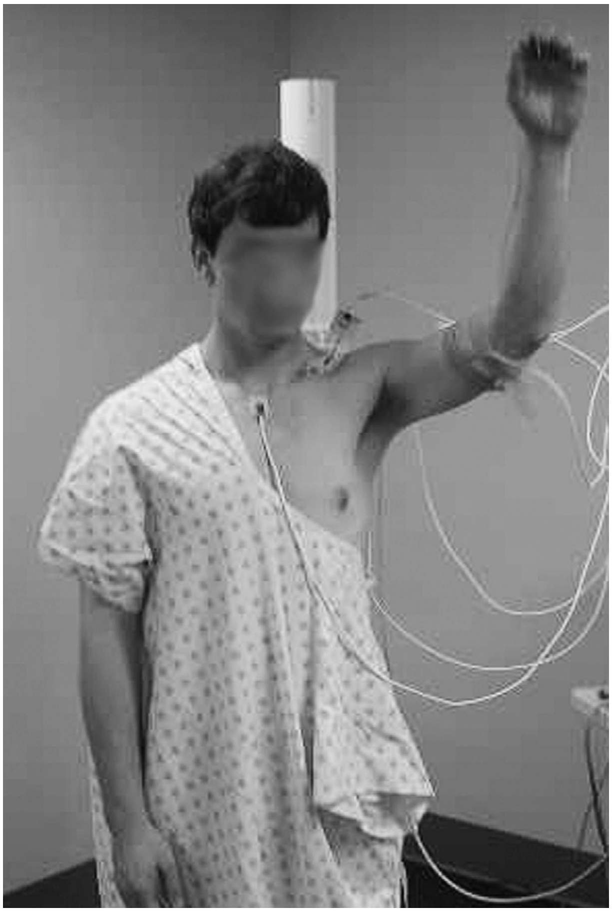

Figure 3 Study volunteer elevates arm in overhead reaching.

Reported ratios have ranged from as low as 1.25:1 to as high as 7.29:1 for different increments of motion, with greater variability early in the motion. Finally, activities of daily living do not occur in constrained planes; therefore, we studied a plane that the participant self-selected to better replicate actual daily shoulder motion.

The purpose of this study was to quantify the relationship of the scapula and the humerus in 3D during unconstrained raising and lowering of the arm overhead. Our null hypothesis was that there would be no significant difference in the rhythm between the raising and lowering of the arm or between portions of the range of motion that occur.

Materials and methods

These results represent a subset of specific motions, not previously published, performed as part of a more comprehensive analysis of shoulder motion in asymptomatic volunteers.[16] Informed consent and Human Subjects Institutional Review Board approval at the University of Minnesota were obtained. Volunteers were aged 18 to 60 years, had no prior shoulder problems, no systemic illness, and a normal clinical shoulder when examined by a licensed physical therapist (P. L.).

Surgical technique and system setup

Fluoroscopy (MiniView 6800 Mobile Imaging System, General Electric Medical Systems, Milwaukee, WI) was used to guide placement of 2.5-mm terminally threaded stainless steel pins, which were inserted using sterile technique with local anesthesia. The pins engaged the far cortex of the scapular spine, distal clavicle, and lateral humerus at the deltoid insertion. The arms of all participants were put through a full range of motion after placement to ensure that no skin tension contributed to pin deflection or limited shoulder motion.

Electromagnetic sensors were rigidly fixed to the bone pins to record active motion. A surface sensor was taped to the sternum as a thoracic reference marker. During testing, motion was recorded by the Flock of Birds mini-bird electromagnetic 3D tracking system (Ascension Technology, Burlington, VT) attached to the pins. This sensor has 6° of freedom and allows recording of movement and rotation in all planes at a sampling rate of 100 Hz per sensor. The reported transmitter system resolution is 0.1° and 0.25 mm.[2,21] Motion Monitor Software (Innovative Sports Training, Chicago, IL) calculated receiver position and orientation along the transmitter axis as well as relative to other reference frames. An integrated digitizing stylus was used to digitize anatomic landmarks with the participants standing relaxed to establish anatomic coordinate systems consistent with the recommendations of the International Society of Biomechanics (ISB) shoulder protocol,[27] except that the acromioclavicular joint was used rather than the posterolateral acromion.[25] The digitized bony landmarks were then used to convert the sensor axes to anatomic axes.

Volunteers were instructed to raise their arms as if reaching for an object on a high shelf (Figure 3). No attempt was made to control plane of motion or height of reaching (participants self-selected their reaching plane and elevated reach position). Two repetitions were completed for each participant, with each repetition consisting of raising and lowering of the arm for a 3-second count.

At the completion of the entire comprehensive shoulder motion study, the pins were removed and the incisions were closed. The volunteers were seen in follow-up at 7 to 10 days for an incision check.

Before pin placement, a subset of 6 volunteers performed the same unconstrained reaching motion using standard surface sensor placements for the humerus and thorax[14] to determine the effects of pin placement on the participant's general motion pattern, maximum elevation during reaching over head, and self-selected plane of elevation.

Data analysis

Angular values for the scapula relative to the thorax were determined using the ISB recommended rotation sequences,[27] along with a humerus relative to the scapula rotation sequence of glenohumeral elevation angle, plane of glenohumeral elevation, and glenohumeral axial (internal/external) rotation (x, z,′ y,″ Cardan angles).[14] Continuous data were recorded for scapular internal rotation, scapular upward rotation, scapular tilting (Figure 1), humerothoracic elevation, glenohumeral elevation (relative to the scapula), glenohumeral elevation plane (anterior or posterior to the scapular plane, Figure 2), and glenohumeral internal/external rotation and were exported from the Motion Monitor software and saved as spreadsheets in Excel (Microsoft, Redmond, WA).

Table I Glenohumeral/scapulothoracic ratios for arm elevation and arm lowering movements for each volunteer at intervals throughout the arc of reaching overhead motion.

Volunteer	Phase	Min-Max	30°-Max	Min-30°	30°-60°	60°-90°	90°-120°
1	Raising	2.10	2.01	2.31	2.49	1.91	2.30
	Lowering	2.10	1.68	3.72	2.59	1.52	1.65
2	Raising	2.11	2.01	6.55	2.18	1.91	2.17
	Lowering	2.16	1.80	8.37	3.03	1.38	2.01
3	Raising	2.12	2.03	3.14	1.98	2.49	2.10
	Lowering	2.15	2.48	2.20	1.40	2.50	3.49
4	Raising	2.59	2.73	2.15	2.20	3.55	2.5
	Lowering	2.80	3.14	2.07	2.34	3.05	4.06
5	Raising	2.48	2.74	1.59	2.10	2.75	2.68
	Lowering	2.48	3.44	0.96	2.40	3.27	6.28
6	Raising	1.65	1.48	5.07	2.22	1.60	1.04
	Lowering	1.43	1.00	2.02	1.60	0.61	1.75
7	Raising	3.36	3.27	3.86	3.44	3.94	2.64
	Lowering	3.88	3.65	3.35	4.02	3.13	4.23
8	Raising	2.27	1.81	7.89	4.16	3.37	1.43
	Lowering	2.42	1.89	5.43	3.32	1.83	1.61
9	Raising	2.42	2.30	4.85	2.51	2.53	3.00
	Lowering	3.36	3.87	0.69	5.47	3.50	3.87
10	Raising	2.09	2.11	4.58	1.64	2.17	2.31
	Lowering	2.22	2.17	2.02	1.56	2.43	2.37
11	Raising	2.38	2.77	1.38	1.58	2.17	4.64
	Lowering	3.21	4.17	0.31	2.64	3.95	5.03
12	Raising	2.90	2.45	1.11	1.86	4.17	3.14
	Lowering	2.97	3.46	0.86	2.79	5.90	4.75
Mean ± SD	Raising	2.37 ± 0.44	2.31 ± 0.50	3.71 ± 2.15	2.36 ± 0.75	2.71 ± .85	2.50 ± 0.90
Mean ± SD	Lowering	2.60 ± 0.67	2.73 ± 1.02	2.67 ± 2.31	2.76 ± 1.14	2.76 ± 1.40	3.43 ± 1.54

The ratio of glenohumeral elevation relative to scapular upward rotation was determined by calculating the slope of the line using scapular upward rotation as the X value and glenohumeral elevation as the Y value (Excel slope function, calculating the slope of the linear regression line). The ratio was calculated from minimum to maximum humerothoracic angle and maximum to minimum angle of each repetition for each participant, as well as in 30° increments (minimum-30°, 30°-60°, 60°-90°, and 90°-120°) during the raising and lowering phases of the repetitions. For the purpose of this study, "raising" was defined as the phase during which the arm was actively raised until maximum elevation, and "lowering" was considered the phase from maximum elevation to the starting position. Ratios were also calculated for the initial portion of the motion cycle (minimum-30°), the portion of the cycle described by Inman et al[8] as the setting phase for abduction (Table I). During our analysis, values obtained for scapular upward rotation, glenohumeral elevation, and glenohumeral external rotation were actually negative based on axis orientation. These values were multiplied by -1 to facilitate clinical correlation and interpretation. Pain scores from 0 to 10 on a numeric rating scale were recorded for each movement during this study.

Statistical analysis

Data values for scapular internal rotation, scapular upward rotation, scapular tilting (all relative to the thorax), glenohumeral elevation, plane of elevation, and internal/external rotation relative to the scapula were averaged across all participants at 5° increments. At each increment, descriptive statistics were calculated. Descriptive statistics across participants were also determined for both the invasive testing and the subset of volunteers for whom humerothoracic motion data were available before pin placement.

For overall ratio data, incremental ratio data, and angular data, a repeated measure analysis of variance was calculated (NCSS, Kaysville, UT) with appropriate factors for each. All analyses used a significant $\alpha = 0.05$ and Tukey-adjusted follow-up comparisons for pairwise differences. Pearson correlations were also computed for the subset of 6 participants in whom humerothoracic elevation before pin placement was compared with values during invasive testing with pins in place.

Results

There were 12 volunteers (7 men and 5 women) with an average age of 29.3 ± 6.8 years, height of 1.74 ± 0.08 meters, and weight of 77.5 ± 13.8 kg. Nondominant arms were tested for 10 of the 12 participants, with 3 right and 9 left shoulders undergoing testing. Pain scores averaged 1.4 points (range, 0-3 points) on a 10-point scale during measurement, and no participants had to limit their overhead reach due to pain or pin placement. No participant had to stop the investigation due to shoulder discomfort. There were no postprocedural complications.

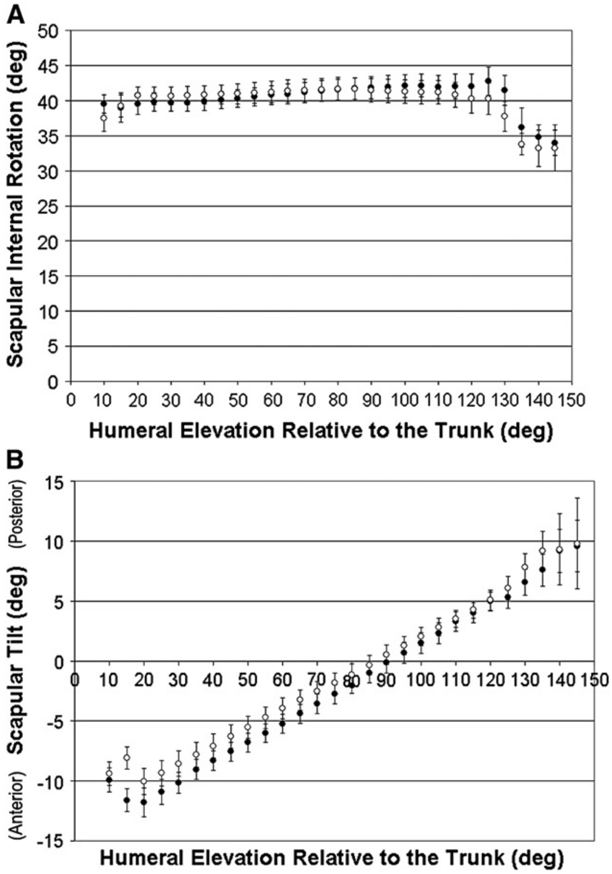

Figure 4 **(A)** Mean scapular internal rotation during humerothoracic elevation (●) and lowering (○) is shown with the standard error. **(B)** Mean scapular tilting during humerothoracic elevation (●) and lowering (○) is shown with the standard error. Posterior tilting is positive.

The average humerothoracic plane of elevation chosen by the participants during overhead reaching was 63.3° ± 7.0° forward of the coronal plane of the trunk, and the average peak elevation was 132.9° ± 9.9°. For the subset of 6 participants, motion during invasive testing was consistent with motion before pin placement. The average plane of elevation and peak elevation during invasive testing were within 2° of these same values compared with overhead reaching tested before pin placement. Humeral elevation motion with and without pins placed had a correlation (*r*) of 0.9, indicating excellent consistency between invasive and noninvasive testing.

Scapulohumeral rhythm

A significant difference ($P < .04$) was documented for the scapulohumeral rhythm between raising and lowering motions (30°-maximum), with glenohumeral elevation to scapular upward rotation ratios of 2.3 and 2.7 respectively (Table I). This difference represents a greater overall scapular contribution during the raising of the arm. For every 1° of glenohumeral elevation, the scapula rotated upward 0.43° across the entire motion arc for overhead reaching and rotated downward 0.37° for every degree the humerus was lowered ($P < .04$). The average scapular upward rotation increased significantly during overhead reaching from 11.4° ± 5.8° to a maximum of 48.6° ± 4.0° ($P < .05$). The glenohumeral elevation values significantly increased from −7.4° ± 5.0° (adducted) at minimum to 96.9° ± 5.5° (abducted) at maximum humerothoracic elevation ($P < .05$).

To determine the relationship between glenohumeral and scapulothoracic motion during different increments of the motion arc, the ratio was also calculated in 30° increments between the starting position and 120° (ie, minimum-30°, 30°-60°, etc; Table I). Ratio differences during increments of motion reflect raising vs lowering of the arm ($P < .004$). During raising of the arm, the glenohumeral contribution to scapulohumeral rhythm was greatest for the min° to 30° increment and decreased as the humerothoracic angle increased. In pair-wise follow-up comparisons, the scapulohumeral rhythm during the minimum° to 30° increment was significantly higher than the values during the 30° to 60° and the 90° to 120° motion increments ($P < .05$; Table I).

Additional scapulothoracic angular values

As the arm was raised, the average scapular internal rotation increased from its minimum until the humerothoracic elevation angle reached 125° (Figure 4, *A*). From that point, it decreased until the point of maximum elevation. This pattern was mirrored as the arm was lowered. At 130° of humerothoracic elevation, scapular internal rotation was increased for arm lowering, followed by a gradual decrease until the minimum humerothoracic elevation. There was no significant difference between raising and lowering the arm for this variable. The minimum value for scapular internal rotation was 33.2° ± 5.2° and the maximum was 42.8° ± 8.7° ($P < .05$).

During raising and lowering of the arm, average scapular tilting followed a linear pattern between 20° and the maximum, posteriorly tilting as the angle of humerothoracic elevation increased (Figure 4, *B*). The scapula was maximally tilted 11.8° ± 4.9° anteriorly at 15° of humerothoracic elevation and reached a maximum posterior tilt of 9.8° ± 7.5° at 145° of humerothoracic elevation, resulting in a change of 21.6° of total posterior tilting during overhead reaching of the arm ($P < .05$). Scapular tilting was not significantly different between raising and lowering the arm.

Additional glenohumeral angular values

The glenohumeral plane of elevation at the initiation of humerothoracic elevation was slightly anterior to the scapular plane and increased progressively until roughly 70° to 80° of humerothoracic elevation, reaching

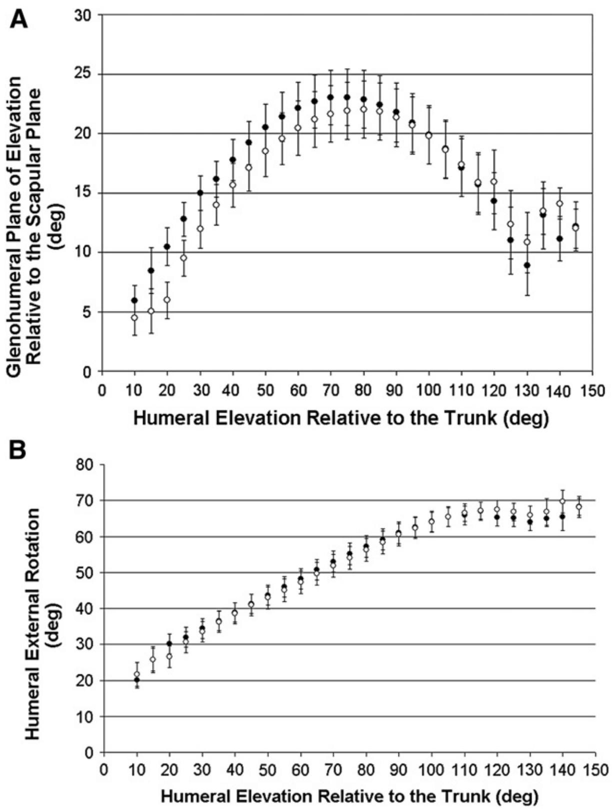

Figure 5 **(A)** Mean glenohumeral plane of elevation relative to the scapular plane during humerothoracic elevation (●) and lowering (○) is shown with the standard error. Anterior to the scapular plane is positive. **(B)** Mean glenohumeral external rotation relative to the scapula during humerothoracic elevation (●) and lowering (○) is shown with the standard error. External rotation is positive.

a maximum of 23.0° ± 11.6° in front of the plane of the scapula (significant angular differences, $P < .05$; Figure 5, *A*). At 70° to 80° of humerothoracic elevation, although the humerus continued to be elevated, the plane of glenohumeral elevation moved toward the scapular plane. The minimum glenohumeral plane of elevation was 4.5° ± 4.7° anterior to the scapular plane. The graph for plane of elevation vs humerothoracic elevation had a parabolic shape (Figure 5, *A*). The glenohumeral elevation and lowering motion curves followed this pattern, without significant differences between raising and lowering the arm. Despite the changes in the plane of elevation across the total arc of motion, the average glenohumeral plane of elevation remained anterior to the scapular plane throughout the course of both raising and lowering the arm.

As the arm was elevated from its initial position, the humerus externally rotated with respect to the scapula (Figure 5, *B*). External rotation of the humerus with respect to the scapula plateaued as the arm reached 110° elevation. No significant difference was observed in external rotation of the humerus with respect to the scapula between elevation and lowering movements. There was a significant difference between the minimum (20.1° ± 11.4°) and maximum (69.7° ± 6.4°) external rotation of the humerus during arm elevation ($P < .05$).

Discussion

To fully treat shoulder pathology, it is important to understand 3D shoulder motion because abnormal scapular kinematics are common in various clinical settings.[14,26] The profound effect that abnormalities of the scapular rhythm have on the entire shoulder girdle is just beginning to be understood. We found shoulder motion followed a complex but consistent pattern. During elevation, the scapula tilted posteriorly, rotated upward, and rotated externally at the end of the arc of elevation. Concurrently, the humerus elevated and externally rotated relative to the scapula. This rotation of the scapula relative to the thorax has been previously described.[10,18,23] Finally, the plane of humeral elevation relative to the scapular plane increased anteriorly until midway through the elevation, at which point it moved back toward the scapular plane until maximum elevation.

Scapulohumeral rhythm during reaching demonstrated small but significant differences between raising and lowering of the arm overhead, resulting in rejection of the null hypothesis. We found that the ratios between participants for this range of motion were remarkably well reproduced, although standard deviations tended to be higher between participants during lowering of the arm. Furthermore, the humerus and scapula followed a consistent and predictable pattern of motion relative to each other during overhead reaching. The minimum to 30° increment of motion for raising the arm overhead demonstrated the highest variability and also showed the highest ratio in our series. Inman et al[8] stated that the 0° to 30° increment for abduction and the 0° to 60° increment for flexion were highly variable between participants and termed it the setting phase; however, they did not provide any ratio data for these setting phases.

Our study found the mean scapulohumeral rhythm from 30° to maximum ranged from 2.3:1 to 2.7:1 when raising and lowering the arm, respectively. We believe that our consistent results are normative data for 3D overhead reaching that can be used to compare to abnormal scapular kinematics.

The increment of humerothoracic elevation from minimum to 30° proved to have the most variability in our study. Inman et al[8] described similar variability and termed this segment the ‘‘setting phase.’’ However, the Inman et al study also documented differences in the region of variability for forward elevation and abduction. Because our study did not control the plane of elevation, this makes direct comparison with prior studies difficult.

Doody et al[4] postulated that the scapula was being stabilized during the early phases of motion when the arm was under the least resistance. This may be accurate; however, it may also be true that each individual initiates reaching from a variable scapular rest position or with a different pattern of scapulothoracic muscle activation. After the humerus and scapula are fully engaged, at approximately 30° of humerothoracic elevation, the relationship follows a more consistent pattern. With the exception of the ''setting phase,'' the Inman group[8] suggested the glenohumeral joint contributed 2° for every 1° contributed by the scapulothoracic articulation in both abduction and forward elevation. Further studies have led to different conclusions with respect to scapulohumeral rhythm, with numbers for the overall ratio ranging from 1.25:1 to 2.5:1.[4,5,18,20,23]

Our study has some limitations. First, the use of invasive techniques could have caused pain from pin insertion that altered the shoulder motion of these asymptomatic participants. We believe that the participants' low pain ratings, similar motion ratios, and similar values from noninvasive testing make it highly unlikely that any significant alteration of shoulder motion occurred due to pain from the pins. Pin placement, however, did inhibit terminal glenohumeral internal/external rotation in 90° abduction in some participants, which limited our ability to collect internal/external rotation data on the far end ranges of motion of the shoulder girdle. However, no participants had limitations in axial rotations of the arm occurring during raising the arm overhead as assessed in this report.

We did not use a bone marker for thoracic location. Unlike the skin motion over the humerus, clavicle, and scapula, we believe the skin over the sternum is immobile enough to make a skin sensor adequate for location determination. In addition, this marker is simply a reference point because the sternum is not a moving part of the shoulder girdle during motion.

Finally, one could argue that the patient self-selected plane of motion limits the study. In a standard orthopedic physician assessment, forward flexion range of motion is often assessed as a nonconstrained (nonplanar) motion overhead.[24] The lack of any increase in-between participant variation during unconstrained overhead reaching compared with traditional planar elevation studies[4,14,18] suggests that the assessment of unconstrained reaching may be more practical and functional in both the research and clinical settings. Also worth noting is that the average self-selected plane (63°) was slightly closer to a constrained scapular abduction plane of 40° than to a constrained flexion plane of 90°.

Conclusions

Treatment of shoulder pathology requires a solid understanding of the motions of the components of the shoulder girdle during normal activities. The recognition that the scapula has a consistent pattern of motion with shoulder elevation (posterior tilting, upward rotation, and external rotation near the end range of motion) allows a better description of the abnormal motion seen in shoulder pathologies. Numerous studies have tried to explore the relationship between the complex motion of the glenohumeral joint and the scapulothoracic articulation. This study sheds further insight into this complex interplay, allowing further understanding and comparison with noninvasive studies that may follow. To the best of our knowledge, this is also the first study to evaluate scapular rhythm in a participant's self-selected plane, which better mimics the daily activities that are limited by many shoulder pathologies.

Furthermore, the recognition that there is a difference between the ratios with raising and lowering of the arm may enable better development of eccentric and concentric training programs for improvement of scapular kinematics during recovery from injury and surgery. The higher values determined during lowering the arm may also relate to the anecdotal reporting that excess scapular motion in patients may be easier to observe when patients are lowering rather than raising the arm overhead.

Finally, increasing our understanding of the normal movements of the scapula and its relation to the humerus during normal daily activities, such as overhead reaching, could have ramifications for physical therapy programs, postsurgical rehabilitation, and potentially even implant design for pathologies related to abnormal scapular motion. Further research will investigate other motions of the shoulder with other movements, as well as dynamic testing of symptomatic patients.

Acknowledgment

The authors acknowledge Cort J. Cieminski, MS, Vandana Phadke, MS, Mike McGinnity, RN, and Kelley Kyle, CST/CFA, for their assistance in data collection.

Disclaimer

This study was supported by National Institutes of Health (NIH) grant No. K01HD042491 from the National Institute for Child Health and Human Development (NICHD). The content is solely the responsibility of the authors and does not reflect the views of NICHHD or NIH.

References

1. Bourne DA, Choo AM, Regan WD, MacIntyre DL, Oxland TR. Three-dimensional rotation of the scapula during functional movements: an in vivo study in healthy volunteers. J Shoulder Elbow Surg 2007;16:150-62.
2. Bull AM, Berkshire FH, Amis AA. Accuracy of an electromagnetic measurement device and application to the measurement and description of knee joint motion. Proc Inst Mech Eng [H] 1998;212:347-55.
3. de Groot JH, Brand R. A three-dimensional regression model of the shoulder rhythm. Clin Biomech 2001;16:735-43.

4. Doody SG, Freedman L, Waterland JC. Shoulder movements during abduction in the scapular plane. Arch Phys Med Rehabil 1970;51:595-604.
5. Freedman L, Munro RR. Abduction of the arm in the scapular plane: scapular and glenohumeral movements. A roentgenographic study. J Bone Joint Surg Am 1966;48:1503-10.
6. Harryman D, Sidles JA, Harris S. Laxity of the normal glenohumeral joint: a quantitative in vivo assessment. J Shoulder Elbow Surg 1992; 1:66-76.
7. Hogfors C, Peterson B, Sigholm G, Herberts P. Biomechanical model of the human shoulder joint—II. The shoulder rhythm. J Biomech 1991;24:699-709.
8. Inman VT, Saunders JB, Abbott LC. Observations on the function of the shoulder joint. J Bone Joint Surg 1944;26:1-26.
9. Karduna AR, McClure PW, Michener LA, Sennett B. Dynamic measurements of three-dimensional scapular kinematics: a validation study. J Biomech Eng 2001;123:184-90.
10. Koh TJ, Grabiner MD, Brems JJ. Three-dimensional in vivo kinematics of the shoulder during humeral elevation. J Applied Biomech 1998;14:312-26.
11. Limpisvasti O, El Attrache NS, Jobe FW. Understanding shoulder and elbow injuries in baseball. J Am Acad Orthop Surg 2007;15:139-47.
12. Lin JJ, Lim HK, Yang JL. Effect of shoulder tightness on glenohumeral translation, scapular kinematics, and scapulohumeral rhythm in subjects with stiff shoulders. J Orthop Res 2006;24:1044-51.
13. 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.
14. Ludewig PM, Cook TM. Alterations in shoulder kinematics and associated muscle activity in people with symptoms of shoulder impingement. Phys Ther 2000;80:276-91.
15. Ludewig PM, Cook TM, Shields RK. Comparison of surface and bone-fixed measurement of humeral motion. J Applied Biomech 2002; 18:163-70.
16. Ludewig PM, Phadke V, Braman JP, Hassett DR, Cieminski CJ, LaPrade RF. Motion of the shoulder complex during multiplanar humeral elevation. J Bone Joint Surg Am 2009;91:378.
17. 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;29:574-83.
18. 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;10:269-77.
19. 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;27:125-33.
20. Mell AG, LaScalza S, Guffey P, Ray J, Maciejewski M, Carpenter JE, et al. Effect of rotator cuff pathology on shoulder rhythm. J Shoulder Elbow Surg 2005;14(1 suppl S):58S-64.
21. Milne AD, Chess DG, Johnson JA, King GJ. Accuracy of an electromagnetic tracking device: a study of the optimal range and metal interference. J Biomech 1996;29:791-3.
22. Pearl ML, Harris SL, Lippitt SB, Sidles JA, Harryman DT, Matsen FA. A system for describing positions of the humerus relative to the thorax and its use in the presentation of several functionally important arm positions. J Shoulder Elbow Surg 1992;1:113-8.
23. Poppen NK, Walker PS. Normal and abnormal motion of the shoulder. J Bone Joint Surg Am 1976;58:195-201.
24. Richards RR, An KN, Bigliani LU, Friedman RJ, Gartsman GM, Gristina AG, et al. A standardized method for assessment of shoulder function. J Shoulder Elbow Surg 1994;3:347-52.
25. van der Helm FC, Pronk GM. Three-dimensional recording and description of motions of the shoulder mechanism. J Biomech Eng 1995;117:27-40.
26. Warner JJ, Micheli LJ, Arslanian LE. Scapulothoracic motion in normal shoulders and shoulders with glenohumeral instability and impingement syndrome. A study using Moire topographic analysis. Clin Orthop Relat Res 1992;285:191-9.
27. Wu G, van der Helm FC, Veeger HE, Makhsous M, Van Roy P, Anglin C, et al. International Society of Biomechanics. 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;38:981-92.