

Effect of Plane of Arm Elevation on Glenohumeral Kinematics

A Normative Biplane Fluoroscopy Study

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Background: Understanding glenohumeral motion in normal and pathologic states requires the precise measurement of shoulder kinematics. The effect of the plane of arm elevation on glenohumeral translations and rotations remains largely unknown. The purpose of this study was to measure the three-dimensional glenohumeral translations and rotations during arm elevation in healthy subjects.

Methods: Eight male subjects performed scaption and forward flexion, and five subjects (three men and two women) performed abduction, inside a dynamic biplane fluoroscopy system. Bone geometries were extracted from computed tomography images and used to determine the three-dimensional position and orientation of the humerus and scapula in individual frames. Descriptive statistics were determined for glenohumeral joint rotations and translations, and linear regressions were performed to calculate the scapulohumeral rhythm ratio.

Results: The scapulohumeral rhythm ratio was 2.0 ± 0.4 :1 for abduction, 1.6 ± 0.5 :1 for scaption, and 1.1 ± 0.3 :1 for forward flexion, with the ratio for forward flexion being significantly lower than that for abduction ($p = 0.002$). Humeral head excursion was largest in abduction (5.1 ± 1.1 mm) and smallest in scaption (2.4 ± 0.6 mm) ($p < 0.001$). The direction of translation, as determined by the linear regression slope, was more inferior during abduction (-2.1 ± 1.8 mm/90°) compared with forward flexion (0.1 ± 10.9 mm/90°) ($p = 0.024$).

Conclusions: Scapulohumeral rhythm significantly decreased as the plane of arm elevation moved in an anterior arc from abduction to forward flexion. The amount of physiologic glenohumeral excursion varied significantly with the plane of elevation, was smallest for scaption, and showed inconsistent patterns across subjects with the exception of consistent inferior translation during abduction.

Clinical Relevance: When evaluating scapulohumeral kinematics during clinical assessment or for rehabilitation protocols, it is important to take into account and control the plane of arm elevation. Abnormalities in scapular motion may be better evaluated during forward flexion of the arm because greater scapular motion is required for this arm motion.

Understanding glenohumeral motion in normal and pathologic states requires the precise measurement of shoulder joint kinematics. Multiple studies have linked abnormal shoulder joint kinematics with various shoulder disorders including secondary impingement¹⁻⁴, rotator cuff tears^{5,6}, glenohumeral osteoarthritis^{7,8}, labral injury, and glenohumeral instability^{9,10}.

Although shoulder pathology is associated with abnormal kinematics, there is little detailed information about baseline values that can provide reference points for the restoration of normal shoulder kinematics. The most commonly studied parameter for glenohumeral rotation is scapulohumeral rhythm, defined as the ratio between glenohumeral elevation and upward scapulothoracic rotation, which was first reported to be 2:1 by

Disclosure: One or more of the authors received payments or services, either directly or indirectly (i.e., via his or her institution), from a third party in support of an aspect of this work. In addition, one or more of the authors, or his or her institution, has had a financial relationship, in the thirty-six months prior to submission of this work, with an entity in the biomedical arena that could be perceived to influence or have the potential to influence what is written in this work. Also, one or more of the authors has had another relationship, or has engaged in another activity, that could be perceived to influence or have the potential to influence what is written in this work. The complete **Disclosures of Potential Conflicts of Interest** submitted by authors are always provided with the online version of the article.

Inman et al.¹¹. Two types of abnormalities in scapulohumeral rhythm have been recognized in shoulders with pathologic conditions: (1) increased rhythm exacerbating the likelihood of secondary impingement by biomechanically decreasing the volume of the subacromial space^{1,3,12-14}, and (2) decreased rhythm serving as a compensatory method that potentially avoids impingement symptoms and improves rotator cuff function^{4,6-9,15-17}.

There is considerable variation in the magnitude of physiologic glenohumeral translations reported in the literature. Normal in vivo glenohumeral translations ranging from 0.3 to 2.6 mm in the superior-inferior direction have been demonstrated by means of dynamic measurements involving fluoroscopy^{18,19} and static measurements involving radiography^{6,20-23}. Normal in vitro superior shoulder translations of 2.0 to 5.7 mm have been reported^{24,25}. Increased mean in vivo glenohumeral translations of approximately 1.5 mm in patients with symptomatic rotator cuff tears⁶, impingement syndrome²¹, and biceps tenodesis²³ have been reported, with individual increases of up to 6 to 8.9 mm^{6,23}.

In recent years, biplane fluoroscopy has emerged as a highly accurate and precise method to measure in vivo three-dimensional kinematics; this method allows measurement of glenohumeral joint motion to within fractions of a millimeter^{26,27}. Clinically, measurement of the full range of arm elevation is important because arm elevation is a common motion during activities of daily living and athletic activities. It is uncommon for shoulder kinematics in fluoroscopic studies to be reported in all three of the standard planes of arm elevation: abduction (coronal plane elevation), scaption (scapular plane elevation), and forward flexion (sagittal plane elevation). As a result, the relative effect of the plane of elevation on glenohumeral translation and scapulohumeral rhythm remains unknown. Our purpose was to measure three-dimensional glenohumeral translations and rotations during abduction, scaption, and forward flexion in healthy subjects. Our hypothesis was that glenohumeral translations and scapulohumeral rhythm would change with the plane of elevation.

Materials and Methods

Subjects

All participants provided written consent and the study was approved by the institutional review board of the Vail Valley Medical Center. Eight male subjects (Group 1) without a shoulder abnormality performed scaption and forward flexion. These subjects had a mean age (and standard deviation) of 29 ± 6 years, height of 1.84 ± 0.05 m, weight of 87.4 ± 7.8 kg, and body mass index of 25.7 ± 2.2 kg/m². In addition, three male and two female subjects (Group 2) performed abduction. These subjects had a mean age of 41 ± 14 years, height of 1.77 ± 0.09 m, weight of 86.5 ± 22.9 kg, and body mass index of 27.2 ± 5.0 kg/m². The subjects in Group 2 had undergone an isolated biceps tenodesis procedure on their contralateral shoulder. Data for Group 2 were originally collected for a previous study comparing glenohumeral translations between the healthy and tenodesed shoulders of these subjects²⁸. Only the healthy shoulder was analyzed in the present study. Thus, a total of eight right shoulders (all dominant) and five left shoulders (all nondominant) were analyzed in the present study. All subjects underwent a detailed shoulder examination by a shoulder specialist to exclude any pathologic condition in the shoulder of interest.

Instrumentation

A custom biplane fluoroscopy system was constructed from two synchronized and modified BV Pulsera C-arms (Philips Medical Systems, Best, The Netherlands)

with 30-cm image intensifiers and was used to measure the three-dimensional position and orientation of the humerus and the scapula. The C-arms were modified under appropriate Food and Drug Administration guidelines and Colorado radiation safety regulations. Motions of the shoulder were performed at a distance of approximately 25 cm from the image intensifiers. For Group 1, data were collected at 30 Hz with the x-ray generators in a pulsed fluoroscopy mode (8 milliseconds, 60 mA, approximately 60 kV) and were subsequently analyzed at 10 Hz (i.e., every third frame). For Group 2, following a system upgrade, data were collected at 100 Hz with the x-ray generators operating in a continuous fluoroscopy mode (12 mA, approximately 60 kV) and were then analyzed at 12.5 Hz (i.e., every eighth frame) because the movements were sufficiently slow and the analysis was labor-intensive. Image distortion was corrected by imaging a square grid and then a calibration cube to determine the x-ray focus positions and the relative positioning and orientation of the two fluoroscopes²⁹.

The biplane fluoroscopy system was validated with use of standard validation techniques^{26,30,31}. Kinematic data for four cadaveric shoulders with the soft tissues intact were collected during scaption to simulate the in vivo measurements. These specimens were placed inside the biplane fluoroscopy system in a comparable position and orientation and were elevated from neutral to maximum elevation over a two-second period with use of a pulley system. The data were analyzed in the same manner as described below for the in vivo study. In addition, five tantalum beads (1.6 mm) were inserted into each scapula and each humerus to provide reference measurements. Bias and precision were calculated, in thirty frames³² for each specimen, as the mean and standard deviation of the difference in the measured scapular and humeral positions and rotations relative to the positions and rotations determined by tracking of the beads. The mean biases and precisions were 0.2 ± 0.5 mm, 0.3 ± 0.3 mm, and 0.3 ± 0.4 mm for measurements of anterior-posterior, superior-inferior, and distraction-compression translations, respectively. The mean biases and precisions were $0.1^\circ \pm 0.8^\circ$, $0.2^\circ \pm 0.2^\circ$, and $1.7^\circ \pm 1.2^\circ$ for measurements of the glenohumeral plane of elevation, elevation angle, and internal-external rotation, respectively. As we had expected because of the increased amount of soft tissue, these values were generally slightly higher than those reported in a previous study of the knee using our system (0.2 ± 0.3 mm, -0.1 ± 0.1 mm, and -0.05 ± 0.1 mm for the three translations and $0.1^\circ \pm 0.1^\circ$, $0.3^\circ \pm 0.2^\circ$, $0.1^\circ \pm 0.3^\circ$ for the three rotations)³³, with the exception of glenohumeral internal-external rotation, which was more difficult to measure in the shoulder because of the cylindrical geometry of the humerus. The values were consistent with similar studies using biplane fluoroscopy^{26,27,34,35}.

During the in vivo activities, the motion of the subject's arm and torso was recorded at 120 Hz with use of an optical motion analysis system (Motion Analysis, Santa Rosa, California) to track how the exercises were being performed at a global level; this provided a reference for the local biplane fluoroscopy data. Thirteen retroreflective markers were placed on the subject's trunk, arm, and forearm. However, only the four markers on the left and the right acromion and on the medial and the lateral epicondyle (elbow joint center) were used to calculate the plane of arm elevation relative to the trunk for the frame in which the arm was elevated to 90° . Data collection by the motion analysis system was synchronized with that of the biplane fluoroscopy system.

Procedures

A high-resolution computed tomography (CT) scan of the subject's shoulder was obtained (Aquilion 64, Toshiba America Medical Systems, Tustin, California). The CT scan was used for reconstruction of the three-dimensional geometry of the scapula and the upper one-third of the humerus. The sequence of axial images from the scan (approximate voxel size, $0.5 \times 0.7 \times 0.7$ mm) was obtained at 120 kVp and 200 mA with sharp-bone CT reconstruction.

The subjects in Group 1 performed two standard range-of-motion exercises over their full range of motion: (1) scaption (motion in the scapular plane, 30° to 40° anterior relative to the coronal plane), and (2) forward flexion (motion in the sagittal plane). The subjects were seated with their back straight and their arm hanging by their side. They then elevated their arm over their head as far as possible at an even pace over the course of two seconds, aided by a metronome, while keeping their elbow fully extended with the thumb pointed upwards. The subjects in Group 2 performed abduction (motion in the coronal

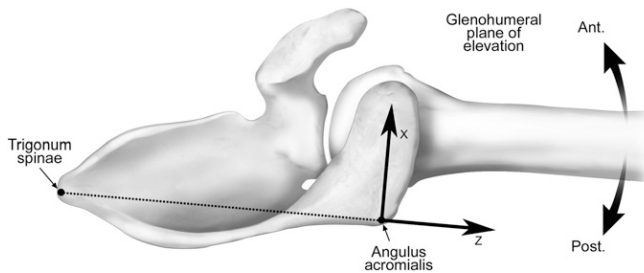


Fig. 1

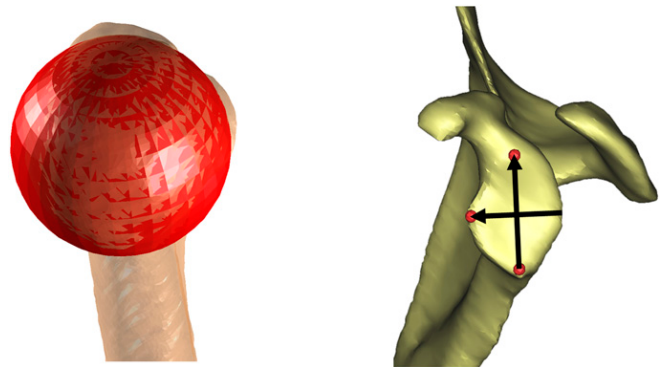


Fig. 2

Fig. 1 Scapular coordinate system and glenohumeral plane of elevation represented in a superior view, with arrows depicting the direction of the anterior and posterior planes. The neutral glenohumeral plane of elevation is determined by the lateral scapular axis (Z), defined as a line running through the angulus acromialis (junction of the posterior and lateral borders of the acromion) and the trigonum spinae scapulae (root of the spine of the scapula). **Fig. 2** The humeral head center (left) is determined by fitting a sphere to the articular surface of the humeral head. The glenoid coordinate system (right) is based on the most superior, inferior, and anterior points on the computed tomography reconstruction.

plane) in a similar fashion. All subjects performed practice runs to become acquainted with the motions. To minimize radiation exposure to the subjects, a single trial was recorded for each motion.

Data Reduction

Data processing consisted of four steps as described previously^{28,36}: reconstruction of the three-dimensional bone geometry of the humerus and scapula from the CT data, coordinate system assignment and geometric transformation, determination of bone positions and orientations in the biplane fluoroscopy data, and postprocessing to extract the shoulder kinematics.

The three-dimensional geometries of the scapula and the humerus were extracted from the CT data (Mimics, Materialise, Plymouth, Michigan). Coordinate systems and three-dimensional glenohumeral rotations were determined by a method that followed the International Society of Biomechanics standard³⁷ as closely as possible. In summary, the lateral axis of the scapula was directed from the trigonum spinae scapulae to the angulus acromialis (Fig. 1), and the anterior axis was perpendicular to the plane of the scapula. The lateral axis of the humerus was directed parallel to a line connecting the medial and lateral epicondyles, which was estimated on the basis of the bicipital groove³⁸. The superior axis of

the humerus was taken as the center line through the canal of the shaft. In addition, a more clinically relevant coordinate system was created to quantify glenohumeral translations. The humeral head center was determined by fitting a sphere to the articular surface of the humeral head (Fig. 2). A glenoid coordinate system was created on the basis of the most superior, inferior, and anterior points on the glenoid rim (Fig. 2). The glenoid center was assumed to lie midway between the most superior and inferior points on the glenoid rim.

Determination of bone position and orientation from the biplane fluoroscopy data was performed for each analyzed frame with use of Model-Based RSA software (Medis Specials, Leiden, The Netherlands)^{31,39}. Contours were automatically extracted from the biplane fluoroscopy images and were manually assigned to the humerus and the scapula. Subsequently, a fully automatic, six-degree-of-freedom contour matching optimization algorithm determined the three-dimensional bone position and orientation. This algorithm optimally matched the detected contours with the projected contours from the imported bone geometries (Fig. 3).

The glenohumeral rotations and translations during the motions were calculated from the optimized bone positions and orientations. Three-dimensional glenohumeral joint rotations were described (using YXY Euler angles³⁷) as (1) the

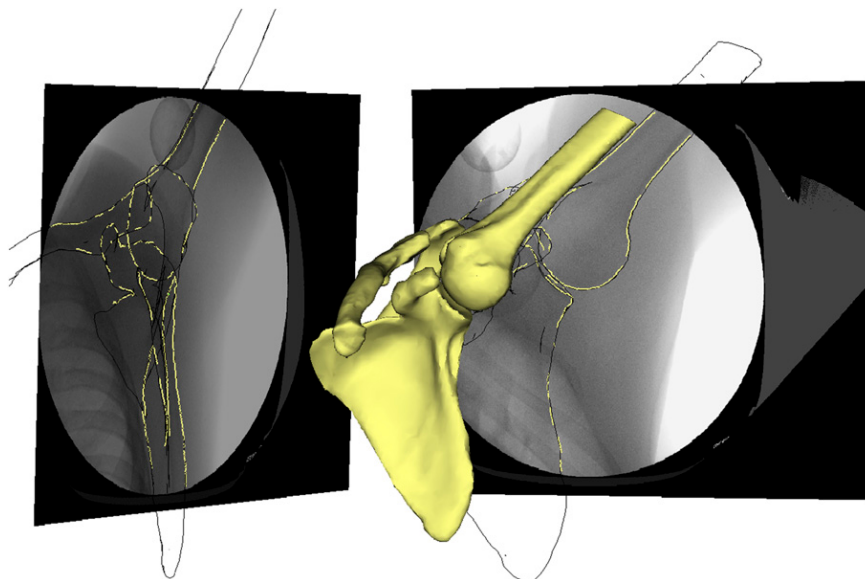


Fig. 3

Matching of bone geometries for an abduction frame. The algorithm matches the detected bone contours (yellow) with the projected bone contours (black).

instantaneous plane of elevation (in front of or behind the scapular plane) about the superior axis of the scapula, (2) the humeral elevation about the anteriorly directed axis of the humerus, and (3) the internal-external axial rotation about the superior axis of the humerus (Fig. 4). Glenohumeral translation was defined as the superior-inferior and anterior-posterior motion of the humeral head center relative to the glenoid coordinate system. Lastly, the arm elevation angle was defined as the angle between the humeral shaft axis and vertical.

For each motion performed by the subject, the time series of the glenohumeral rotations and translations was filtered at 2 Hz. The glenohumeral rotation and translation curves for each motion were analyzed from 20° to 150° of arm elevation. A linear regression analysis was performed to determine the slope (change in glenohumeral elevation/change in arm elevation) and the intercept for the relationship between glenohumeral elevation and arm elevation angle. The slope quantifies how much glenohumeral elevation occurs per degree of arm elevation. Given that arm elevation equals the sum of glenohumeral elevation and upward scapulothoracic rotation (Fig. 4), upward scapulothoracic rotation was then calculated by subtracting the glenohumeral elevation from the arm elevation. Subsequently, scapulohumeral rhythm was determined by calculating the ratio of glenohumeral elevation to upward scapulothoracic rotation¹¹. The mean, standard deviation, maximum, minimum, and total excursion (maximum minus minimum) were calculated for each motion for each translation direction. In addition, linear regression quantified the slope and intercept of the glenohumeral translations as a function of arm elevation. The slope was expressed as the amount of translation per 90° of arm elevation. Lastly, the rotation and translation data as a function of arm elevation were resampled in 10° intervals from 20° to 150° of arm elevation.

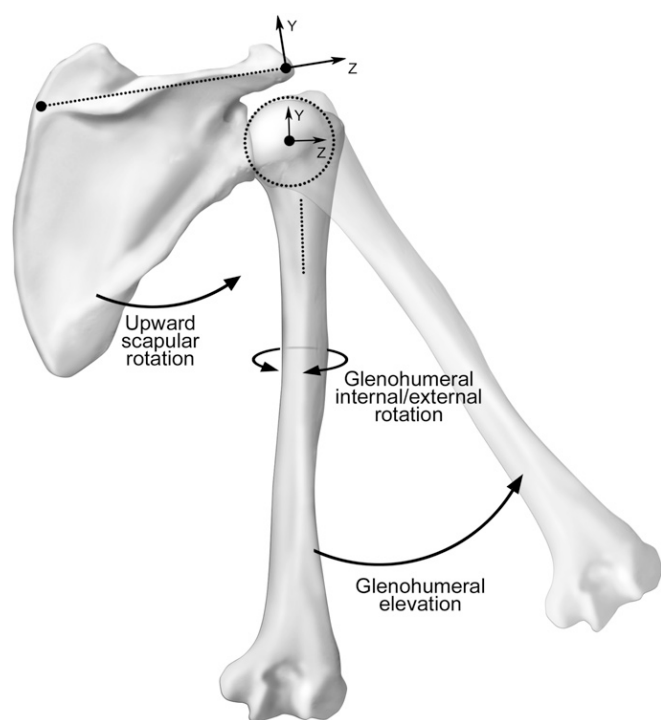


Fig. 4
The scapular and humeral coordinate systems as well as glenohumeral elevation, glenohumeral internal-external rotation, and upward scapular rotation are indicated in a posterior view of a right shoulder. The origin of the humeral coordinate system is located in the center of the humeral head (dotted circle), and the long axis (Y) is determined by calculating the center line of the proximal aspect of the shaft (dotted line).

Statistical Methods

A one-way analysis of variance (ANOVA) with the arm plane of elevation (abduction, scaption, or forward flexion) as the independent variable was performed to analyze the linear regression results, scapulohumeral rhythm, glenohumeral plane of elevation and rotation, arm plane of elevation, and mean, maximum, minimum, and excursion of the anterior-posterior and superior-inferior glenohumeral positions. A *p* value of 0.05 was considered significant. When significant ANOVA results were found, Bonferroni-corrected post hoc comparisons were performed to analyze the specific differences between the elevation planes. A two-way ANOVA with the elevation plane (abduction, scaption, forward flexion) and arm elevation angle (20° to 150° in 10° increments) as the independent variables was performed to statistically analyze the glenohumeral elevation angle as well as anterior-posterior and superior-inferior glenohumeral translations. A one-sample *t* test was used to determine whether regression slope values were significantly different from zero (at the *p* < 0.05 level).

Source of Funding

This work was supported by the Steadman Philippon Research Institute and the Gumbo Foundation. In addition, the Minnesota Medical Foundation supported the Summer Research Internship position of one of the authors. Neither the Gumbo Foundation nor any other corporate sponsorship to our institution played a role in the investigation.

Results

The means for the three glenohumeral rotations as a function of arm elevation angle are shown in Figure 5. The images of the forward flexion trial of one subject were underexposed and the trial had to be excluded from the results. The mean slopes of the glenohumeral elevation regression for the abduction, scaption, and forward flexion curves were 0.66 ± 0.05 , 0.60 ± 0.06 , and 0.52 ± 0.07 , respectively, with the slope for coronal plane abduction being significantly greater than that for forward flexion (*p* = 0.001) (see Appendix). The corresponding scapulohumeral rhythm ratios were 2.0 ± 0.4 :1 for abduction, 1.6 ± 0.5 :1 for scaption, and 1.1 ± 0.3 :1 for forward flexion, with the rhythm for abduction being significantly greater than that for forward flexion (*p* = 0.002). Overall, the glenohumeral contribution to arm elevation decreased as the plane of arm elevation moved anteriorly from the coronal plane (abduction) toward the sagittal plane (forward flexion).

The data demonstrated that the glenohumeral plane of elevation for abduction at 90° of arm elevation, $-11.8^\circ \pm 4.7^\circ$, was similar to that for scaption, $-11.6^\circ \pm 4.9^\circ$, with both planes lying slightly posterior to the plane of the scapula (see Appendix). These motions were also similar globally, with abduction performed at an arm elevation plane of $16.8^\circ \pm 7.9^\circ$ and scaption at $30.1^\circ \pm 8.2^\circ$. Forward flexion was significantly anterior compared with the other two motions, with a glenohumeral elevation plane of $42.4^\circ \pm 12.2^\circ$ and an arm elevation plane of $81.2^\circ \pm 14.7^\circ$ (*p* < 0.001). The results for glenohumeral internal rotation mirrored those for the plane of elevation, with forward flexion demonstrating significantly more internal rotation ($37.2^\circ \pm 15.0^\circ$) compared with scaption ($19.0^\circ \pm 11.9^\circ$) and abduction ($19.5^\circ \pm 9.1^\circ$) (*p* = 0.032) (see Appendix).

The group mean and standard deviation of the descriptive statistics for anterior-posterior glenohumeral translation for all three motions are presented in the Appendix and depicted as a

function of the arm elevation angle in Figure 6. On average, the humeral head was positioned 4 to 5 mm posterior to the midline of the glenoid for all motions. The glenohumeral excursions (total amount of translation) for abduction, scaption, and forward flexion for the group were 1.4 mm, 0.7 mm, and 2.4 mm, respectively, and the between-subject variabilities (i.e., standard deviation averaged across all arm elevation angles) were 2.1 mm, 1.0 mm, and 1.9 mm. When the parameters extracted from the individual curves were analyzed, the minimum (most posterior) position was significantly more posterior for abduction (-7.7 ± 1.2) than for scaption (-5.6 ± 1.0 mm) ($p = 0.025$). In addition, the excursions for all three motions were significantly different from each other ($p < 0.001$), with excursion occurring during abduction (5.1 ± 1.1 mm) being larger than that during flexion (3.6 ± 1.1 mm), which in turn was larger than that during scaption (2.4 ± 0.6 mm). No other significant differences were found.

The group mean and standard deviation of each descriptive statistic for superior-inferior position for each motion are presented in the Appendix, and values are depicted as a function of arm elevation angle in Figure 6. To demonstrate the between-subject variability, the descriptive statistics for the individual subjects and the group mean and standard deviation for the superior-inferior glenohumeral position for scaption are also presented in the Appendix. On average, the humeral head was

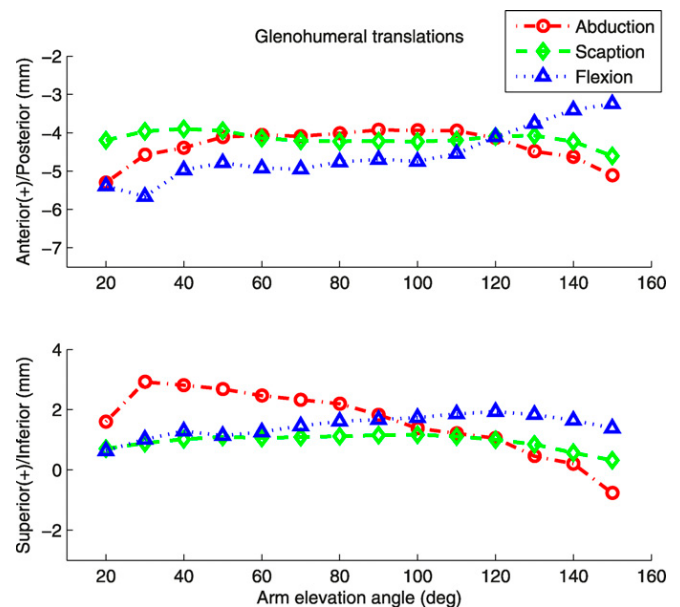


Fig. 6

Mean anterior-posterior and mean superior-inferior position of the humeral head relative to the glenoid as a function of arm elevation angle in the three planes of motion.

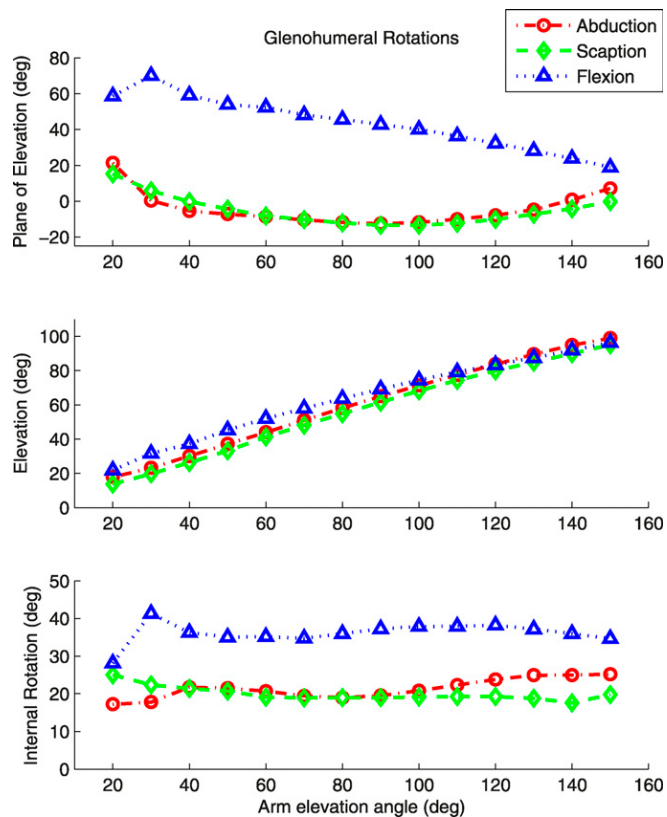


Fig. 5

Mean glenohumeral plane of elevation, elevation angle, and internal rotation as a function of arm elevation angle in the three planes of motion (forward flexion, scaption, and abduction).

positioned 1 to 2 mm superior to the midline of the glenoid for all motions. The glenohumeral excursions for the group for abduction, scaption, and forward flexion were 3.7 mm, 0.9 mm, and 1.3 mm, respectively, and the between-subject variabilities were 2.3 mm, 1.7 mm, and 1.4 mm. The slope of the linear regression curve indicated that translation was significantly more inferiorly directed for abduction (-2.1 ± 1.8 mm/90°) compared with forward flexion (0.1 ± 0.9 mm/90°) ($p = 0.024$) and approached being different from zero ($p = 0.057$). In addition, the two-way ANOVA showed a significant difference between abduction and scaption ($p = 0.017$), with the glenohumeral position during abduction being significantly more superior compared with scaption. No other significant differences were found.

Discussion

This study indicated that changes in the plane of arm elevation affected glenohumeral kinematics in multiple ways, including in glenohumeral translations, glenohumeral elevation, and scapulohumeral rhythm, which confirmed our hypothesis. The scapulohumeral rhythm ratio was significantly smaller for forward flexion than for abduction. Therefore, forward flexion was associated with a greater scapular contribution via upward rotation and relatively less glenohumeral elevation compared with abduction. This difference in scapulohumeral rhythm suggests that scapular motion abnormalities may be better examined in forward flexion because any abnormalities may be more apparent. This finding supports a similar recommendation in a recent clinical study⁴⁰.

The glenohumeral translations indicated that, on average, the humeral head was positioned posteriorly and superiorly on the glenoid. During shoulder motion, the total humeral

head excursion was greatest in abduction and smallest in scaption. Group mean excursion was always less than the between-subject variability, with the exception of superior-inferior excursion during abduction (3.7 mm compared with 2.3 mm). The individual excursions, and especially that for scaption, were relatively small compared with the mean male glenoid size of 27.4×37.5 mm³⁴. The excursions equaled 18.6%, 8.8%, and 13.1% of the glenoid size for abduction, scaption, and forward flexion, respectively, in the anterior-posterior direction and 11.2%, 6.7%, 8.0% in the superior-inferior direction. The directions of the translations, as determined by the linear regression slope, were inconsistent among subjects and were not in a specific direction, with the exception of inferior translation during abduction. The data clearly showed that the plane of arm elevation needs to be controlled in research and clinical settings to accurately assess and clinically follow scapulohumeral rhythm and glenohumeral translations in patients with shoulder disorders.

Understanding normal scapulohumeral rhythm is key to identifying and treating clinical shoulder disorders because abnormal shoulder kinematics are routinely measured during clinical examinations and in biomechanical studies involving subacromial impingement, rotator cuff tears, adhesive capsulitis, glenohumeral osteoarthritis, and glenohumeral instability^{1-10,13,14,23,41-44}. In 1944, Inman et al.¹¹ first assigned a value to scapulohumeral rhythm, reporting that scapulohumeral rhythm in healthy subjects performing abduction occurred in a 2:1 ratio. However, ratios ranging from 1.25:1 to 5.3:1 have been subsequently reported with the advent of newer and more accurate measurement techniques^{4,5,12,42,45-52}. Despite these findings, Inman's ratio of 2:1 is still commonly used in educational and clinical settings and was further supported by the present study (which found a ratio of 2.0 ± 0.4 :1 for abduction).

Clinically, these results provide valuable baseline data on both mean translation amplitude and between-subject variability for future studies investigating glenohumeral translations in other patient populations such as those with various forms of impingement, rotator cuff disease, instability, and arthritis. Indeed, one of the theories regarding glenohumeral arthritis is that the etiology involves an increase in shear force that cannot be tolerated by the articular cartilage⁵³. The results of the present study demonstrated that, in a healthy glenohumeral joint, only small excursions of 2.5 mm occur in both principal directions during scaption over the full range of shoulder motion. Therefore, it is unlikely that shoulder translations in healthy shoulders are measureable with use of palpation or skin-based measurement methods. Moreover, the standard deviations for glenohumeral position were greater than the measured excursion amplitudes, indicating that the motion-related translations were smaller than the variations among subjects and can therefore only be measured with advanced imaging techniques. Future studies of patient populations diagnosed with instability and suspected of having increased glenohumeral translations will place the magnitude of clinically relevant translations in perspective.

These results also provide valuable baseline data for computer simulations and in vitro experimentation. In computer

modeling, the glenohumeral joint is commonly modeled as a ball and socket joint⁵⁴⁻⁵⁶. We found that this approximation was accurate to within 2.5 mm for scaption and 5.1 mm for abduction, or within 9% and 19% of the mean glenoid dimension, respectively. Therefore, the ball and socket assumption may be reasonable (with an error of <10%) for the shoulders of healthy subjects during scaption, but it may not be acceptable for other motions or for pathologic conditions. It is unclear what effect this may have on muscular lines of action and moment arms, and developers of computer models need to be mindful when making the assumption of a ball and socket joint for arbitrary motions. The results of the present study also indicated that glenohumeral translations previously reported for some in vitro studies (e.g., 5.7 mm superior translation²⁵) may be excessive and should be treated with caution, as their magnitude is suggestive of loading that is improper for simulating in vivo motion. Therefore, the data from the present study provide a baseline value to be met by in vitro studies that are aimed at replicating physiologic loading of the joint.

The present study has several limitations. First, the scapulohumeral rhythm results were derived solely from the glenohumeral component during arm elevation. Scapulothoracic rotation was not measured directly but was assumed to equal the difference between total arm elevation and glenohumeral elevation. Although this is a simplification, we believe the result to represent a valid estimate for comparing the different motions. Similar methods relying on these relationships have been used in previous studies^{45,46,49,51,52}. Second, abduction did not occur in a purely coronal plane. Even though clinicians confirmed visually during data collection that subjects appeared to be performing the abduction movement appropriately, kinematic results indicated the arm motion to be 17° anterior to the coronal plane. The fact that abduction actually occurred halfway between the scapular plane and the true coronal plane could potentially explain the similarities between our abduction and scaption rotation results. However, significant differences between these motions were still found for the glenohumeral translations. We suggest that future studies use a guide to ensure that motions are performed in the proper planes.

Third, the biplane fluoroscopy methodology used in the study results in radiation exposure. However, fluoroscopy is the most accurate measurement technique to date, and it allows the greatest freedom of movement and the highest frame rates of any technique. Care was taken to keep the amount of radiation as low as possible. This was the reason that only one trial was obtained for each motion. In addition, the lowest technique factors that still allowed sufficient image quality for motion tracking were used. Unfortunately, this resulted in the exclusion of the forward flexion trial of one subject because of underexposure. Lastly, our subject population consisted of two distinct groups, which was not ideal. The data represented the combination of two originally distinct studies into one. The data could have been improved by having an entirely new group of subjects perform all three of the motions. However, this would have exposed additional subjects to radiation. Therefore, existing data were used to estimate the mean values for normal, healthy shoulders, and we believe that both of the included groups accurately represented this population.

In conclusion, this study helped to characterize the dynamic relationship between glenohumeral rotation and translation in healthy individuals during motion in three arm elevation planes. There were significant differences in scapulohumeral rhythm between abduction and forward flexion. Therefore, when evaluating detailed scapulohumeral rhythm kinematics during clinical assessment of shoulder disorders, it is important to take into account and control the plane of arm elevation. The data suggest that evaluation of forward flexion may represent a better method for assessing scapular abnormalities than scaption or coronal plane abduction.

Appendix

eA Tables showing the descriptive statistics for glenohumeral rotation, anterior-posterior and superior-inferior glenohumeral position, and between-subject variability in superior-inferior position during scaption are available with the online version of this article as a data supplement at jbjs.org. ■

NOTE: The authors thank Medis Specials for providing the Model-Based RSA analysis software and Dr. Robert F. LaPrade for his invaluable input on the manuscript. The authors also acknowledge Christopher Dewing, Florian Elser, Jacob Krong, Dan Peterson, Tyler Anstett, and J.D. Paul for their contributions to this investigation.

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