Effect of Plane of Arm Elevation on Glenohumeral Kinematics

A Normative Biplane Fluoroscopy Study

J. Erik Giphart, PhD, John P. Brunkhorst, BA, Nils H. Horn, MD, Kevin B. Shelburne, PhD,
Michael R. Torry, PhD, and Peter J. Millett, MD, MSc

Investigation performed at the Department of BioMedical Engineering, Steadman Philippon Research Institute, Vail, Colorado

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 impingement[1-4], 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.

J Bone Joint Surg Am. 2013;95:238-45 • http://dx.doi.org/10.2106/JBJS.J.01875

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 tears[6], impingement syndrome[21], and biceps tenodesis[23] 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/m^2. 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/m^2. 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 subjects[28]. 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 fluoroscopes[29].

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 frames[32] 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° ± 0.8°, 0.2° ± 0.2°, and 1.7° ± 1.2° 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° ± 0.1°, 0.3° ± 0.2°, 0.1° ± 0.3° 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 × 0.7 × 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

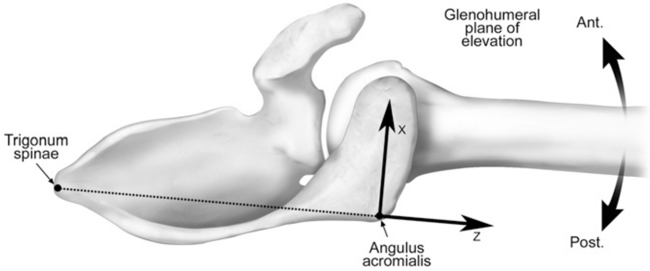

Fig. 1

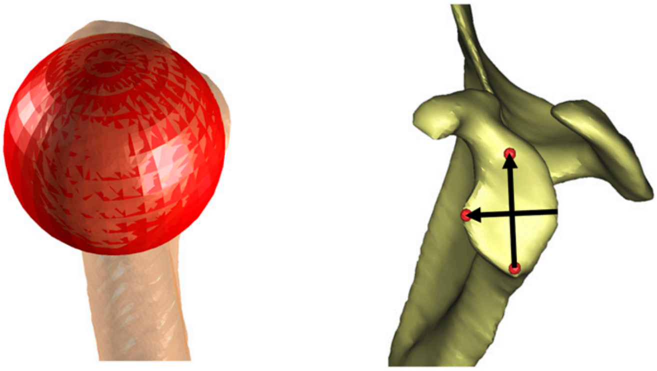

Fig. 2

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 standard[37] 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 groove[38]. 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 angles[37]) as (1) the

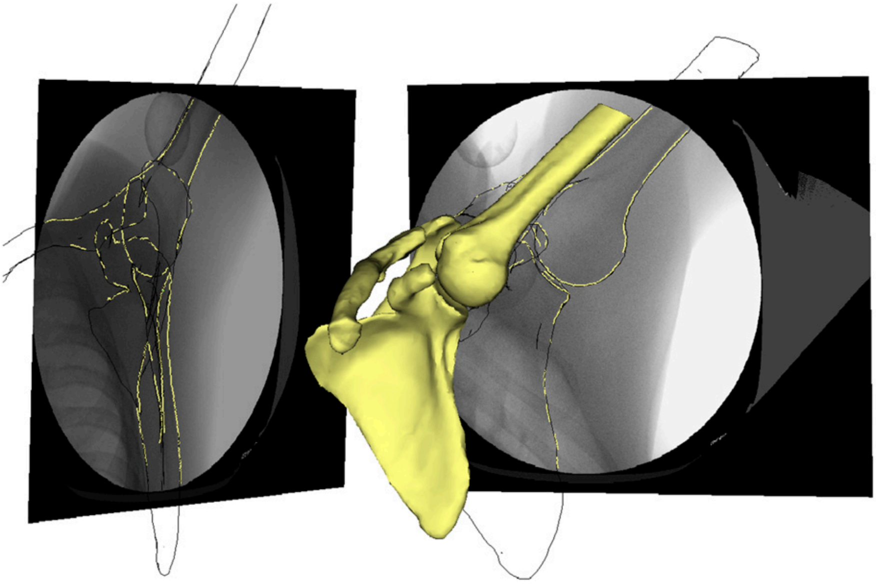

Fig. 3

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 rotation[11]. 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.

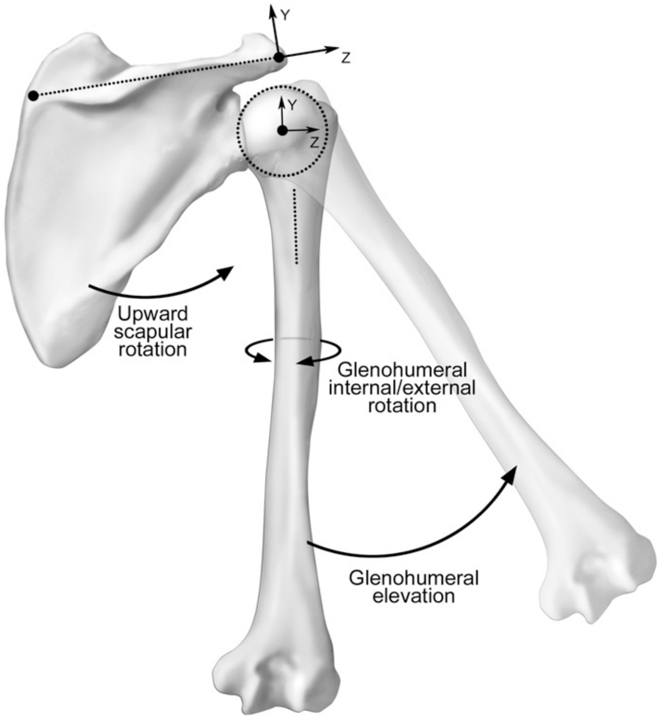

Fig. 4

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° ± 4.7°, was similar to that for scaption, −11.6° ± 4.9°, 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° ± 7.9° and scaption at 30.1° ± 8.2°. Forward flexion was significantly anterior compared with the other two motions, with a glenohumeral elevation plane of 42.4° ± 12.2° and an arm elevation plane of 81.2° ± 14.7° ($p < 0.001$). The results for glenohumeral internal rotation mirrored those for the plane of elevation, with forward flexion demonstrating significantly more internal rotation (37.2° ± 15.0°) compared with scaption (19.0° ± 11.9°) and abduction (19.5° ± 9.1°) ($p = 0.032$) (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 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.

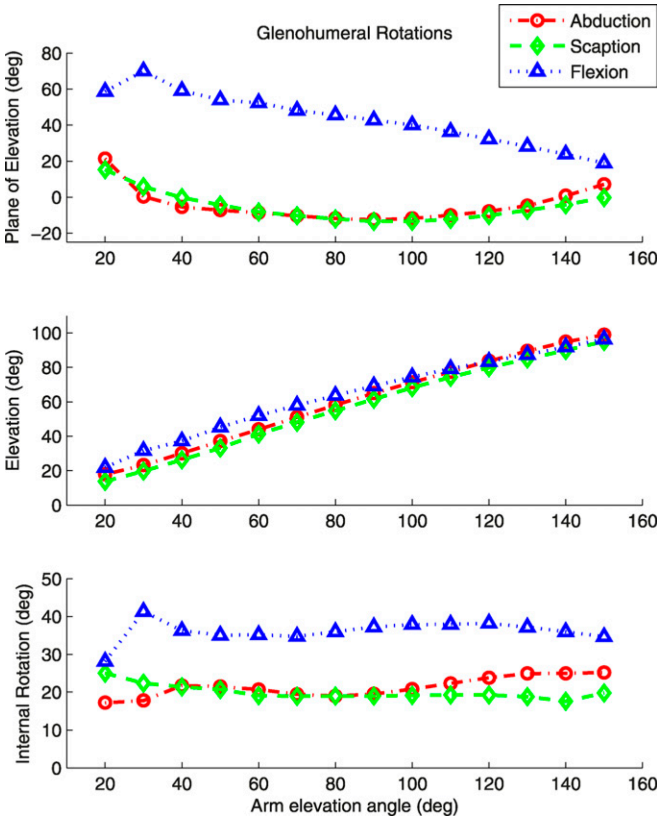

Fig. 5

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).

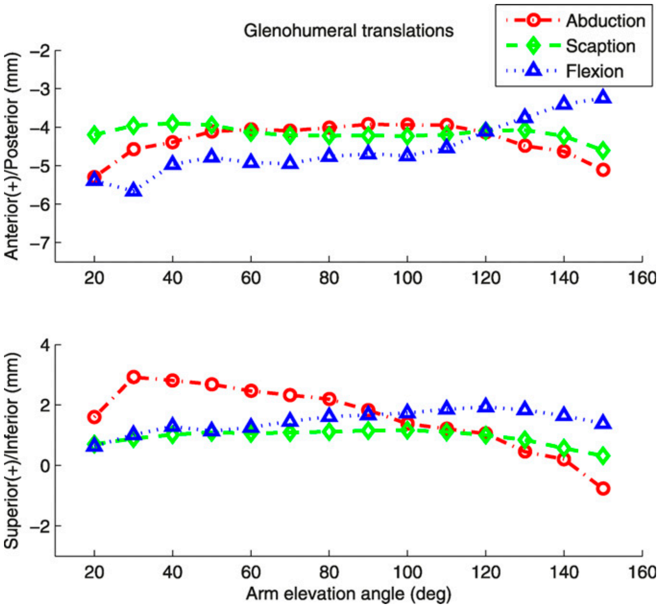

Fig. 6

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.

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 study[40].

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 mm[34]. 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 cartilage[53]. 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 joint[54-56]. 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 translation[25]) 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

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. Pault for their contributions to this investigation.

J. Erik Giphart, PhD
John P. Brunkhorst, BA
Nils H. Horn, MD
Department of BioMedical Engineering,
Steadman Philippon Research Institute,
181 West Meadow Drive,
Suite 1000, Vail, CO 81657.

Kevin B. Shelburne, PhD
Department of Mechanical and Materials Engineering,
the University of Denver, 2390 South York Street,
Denver, CO 80208

Michael R. Torry, PhD
College of Applied Science and Technology,
School of Kinesiology and Recreation,
Campus Box 5120, Illinois State University,
Normal, IL 61790

Peter J. Millett, MD, MSc
The Steadman Clinic, 181 West Meadow Drive,
Suite 400, Vail, CO 81657
E-mail address: drmillett@thesteadmanclinic.com

References

1. Hébert LJ, Moffet H, McFadyen BJ, Dionne CE. Scapular behavior in shoulder impingement syndrome. Arch Phys Med Rehabil. 2002 Jan;83(1):60-9.

2. Ludewig PM, Cook TM. Alterations in shoulder kinematics and associated muscle activity in people with symptoms of shoulder impingement. Phys Ther. 2000 Mar;80(3):276-91.

3. 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 Oct;29(10):574-83; discussion 584-6.

4. 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 May-Jun;10(3):269-77.

5. Poppen NK, Walker PS. Normal and abnormal motion of the shoulder. J Bone Joint Surg Am. 1976 Mar;58(2):195-201.

6. Yamaguchi K, Sher JS, Andersen WK, Garretson R, Uribe JW, Hechtman K, Neviaser RJ. Glenohumeral motion in patients with rotator cuff tears: a comparison of asymptomatic and symptomatic shoulders. J Shoulder Elbow Surg. 2000 Jan-Feb;9(1):6-11.

7. Braman JP, Thomas BM, Laprade RF, Phadke V, Ludewig PM. Three-dimensional in vivo kinematics of an osteoarthritic shoulder before and after total shoulder arthroplasty. Knee Surg Sports Traumatol Arthrosc. 2010 Dec;18(12):1774-8. Epub 2010 Jun 5.

8. Fayad F, Roby-Brami A, Yazbeck C, Hanneton S, Lefevre-Colau MM, Gautheron V, Poiraudeau S, Revel M. Three-dimensional scapular kinematics and scapulohumeral rhythm in patients with glenohumeral osteoarthritis or frozen shoulder. J Biomech. 2008;41(2):326-32. Epub 2007 Oct 18.

9. 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 May;24(5):1044-51.

10. Ogston JB, Ludewig PM. Differences in 3-dimensional shoulder kinematics between persons with multidirectional instability and asymptomatic controls. Am J Sports Med. 2007 Aug;35(8):1361-70. Epub 2007 Apr 9.

11. Inman VT, Saunders JB, Abbott LC. Observations of the function of the shoulder joint. 1944. Clin Orthop Relat Res. 1996 Sep;(330):3-12.

12. Borsa PA, Timmons MK, Sauers EL. Scapular-Positioning Patterns During Humeral Elevation in Unimpaired Shoulders. J Athl Train. 2003 Mar;38(1):12-17.

13. Borstad JD, Ludewig PM. Comparison of scapular kinematics between elevation and lowering of the arm in the scapular plane. Clin Biomech (Bristol, Avon). 2002 Nov-Dec;17(9-10):650-9.

14. 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 Aug;24(2):57-65.

15. Kibler WB. The role of the scapula in athletic shoulder function. Am J Sports Med. 1998 Mar-Apr;26(2):325-37.

16. McQuade KJ, Dawson J, Smidt GL. Scapulothoracic muscle fatigue associated with alterations in scapulohumeral rhythm kinematics during maximum resistive shoulder elevation. J Orthop Sports Phys Ther. 1998 Aug;28(2):74-80.

17. Mell AG, LaScalza S, Guffey P, Ray J, Maciejewski M, Carpenter JE, Hughes RE. Effect of rotator cuff pathology on shoulder rhythm. J Shoulder Elbow Surg. 2005 Jan-Feb;14(1 Suppl S):58S-64S.

18. Bey MJ, Kline SK, Zauel R, Lock TR, Kolowich PA. Measuring dynamic in-vivo glenohumeral joint kinematics: technique and preliminary results. J Biomech. 2008;41(3):711-4. Epub 2007 Nov 9.

19. Nishinaka N, Tsutsui H, Mihara K, Suzuki K, Makiuchi D, Kon Y, Wright TW, Moser MW, Gamada K, Sugimoto H, Banks SA. Determination of in vivo glenohumeral translation using fluoroscopy and shape-matching techniques. J Shoulder Elbow Surg. 2008 Mar-Apr;17(2):319-22. Epub 2007 Dec 26.

20. Chen SK, Simonian PT, Wickiewicz TL, Otis JC, Warren RF. Radiographic evaluation of glenohumeral kinematics: a muscle fatigue model. J Shoulder Elbow Surg. 1999 Jan-Feb;8(1):49-52.

21. Deutsch A, Altchek DW, Schwartz E, Otis JC, Warren RF. Radiologic measurement of superior displacement of the humeral head in the impingement syndrome. J Shoulder Elbow Surg. 1996 May-Jun;5(3):186-93.

22. Teyhen DS, Miller JM, Middag TR, Kane EJ. Rotator cuff fatigue and glenohumeral kinematics in participants without shoulder dysfunction. J Athl Train. 2008 Jul-Aug;43(4):352-8.

23. Warner JJ, McMahon PJ. The role of the long head of the biceps brachii in superior stability of the glenohumeral joint. J Bone Joint Surg Am. 1995 Mar;77(3):366-72.

24. Kelkar R, Wang VM, Flatow EL, Newton PM, Ateshian GA, Bigliani LU, Pawluk RJ, Mow VC. Glenohumeral mechanics: a study of articular geometry, contact, and kinematics. J Shoulder Elbow Surg. 2001 Jan-Feb;10(1):73-84.

25. Wuelker N, Schmotzer H, Thren K, Korell M. Translation of the glenohumeral joint with simulated active elevation. Clin Orthop Relat Res. 1994 Dec;(309):193-200.

26. Bey MJ, Zauel R, Brock SK, Tashman S. Validation of a new model-based tracking technique for measuring three-dimensional, in vivo glenohumeral joint kinematics. J Biomech Eng. 2006 Aug;128(4):604-9.

27. Massimini DF, Warner JJ, Li G. Non-invasive determination of coupled motion of the scapula and humerus—an in-vitro validation. J Biomech. 2011 Feb 3;44(3):408-12. Epub 2010 Nov 4. Erratum in: J Biomech. 2011 Apr 29;44(7):1428.

28. Giphart JE, Elser F, Dewing CB, Torry MR, Millett PJ. The long head of the biceps tendon has minimal effect on in vivo glenohumeral kinematics: a biplane fluoroscopy study. Am J Sports Med. 2012 Jan;40(1):202-12. Epub 2011 Sep 30.

29. Kaptein BL, Shelburne KB, Torry MR, Giphart JE. A comparison of calibration methods for stereo fluoroscopic imaging systems. J Biomech. 2011 Sep 2;44(13):2511-5. Epub 2011 Jul 23.

30. Hurschler C, Seehaus F, Emmerich J, Kaptein BL, Windhagen H. Comparison of the model-based and marker-based roentgen stereophotogrammetry methods in a typical clinical setting. J Arthroplasty. 2009 Jun;24(4):594-606. Epub 2008 Aug 3.

31. Kaptein BL, Valstar ER, Stoel BC, Reiber HC, Nelissen RG. Clinical validation of model-based RSA for a total knee prosthesis. Clin Orthop Relat Res. 2007 Nov;464:205-9.

32. ASTM. E177-08 standard practice for use of the terms precision and bias in ASTM test methods (historical standard). West Conshohocken, PA: ASTM International; 2008.

33. Torry MR, Shelburne KB, Peterson DS, Giphart JE, Krong JP, Myers C, Steadman JR, Woo SL. Knee kinematic profiles during drop landings: a biplane fluoroscopy study. Med Sci Sports Exerc. 2011 Mar;43(3):533-41.

34. Anderst W, Zauel R, Bishop J, Demps E, Tashman S. Validation of three-dimensional model-based tibio-femoral tracking during running. Med Eng Phys. 2009 Jan;31(1):10-6. Epub 2008 Apr 23.

35. Li G, Van de Velde SK, Bingham JT. Validation of a non-invasive fluoroscopic imaging technique for the measurement of dynamic knee joint motion. J Biomech. 2008;41(7):1616-22. Epub 2008 Apr 3.

36. Braun S, Millett PJ, Yongpravat C, Pault JD, Anstett T, Torry MR, Giphart JE. Biomechanical evaluation of shear force vectors leading to injury of the biceps reflection pulley: a biplane fluoroscopy study on cadaveric shoulders. Am J Sports Med. 2010 May;38(5):1015-24. Epub 2010 Mar 22.

37. Wu G, van der Helm FC, Veeger HE, Makhsous M, Van Roy P, Anglin C, Nagels J, Karduna AR, McQuade K, Wang X, Werner FW, Buchholz B; 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 May;38(5):981-992.

38. Balg F, Boulianne M, Boileau P. Bicipital groove orientation: considerations for the retroversion of a prosthesis in fractures of the proximal humerus. J Shoulder Elbow Surg. 2006 Mar-Apr;15(2):195-8.

39. Kaptein BL, Valstar ER, Stoel BC, Rozing PM, Reiber JH. A new model-based RSA method validated using CAD models and models from reversed engineering. J Biomech. 2003 Jun;36(6):873-82.

40. Uhl TL, Kibler WB, Gecewich B, Tripp BL. Evaluation of clinical assessment methods for scapular dyskinesis. Arthroscopy. 2009 Nov;25(11):1240-8.

41. Kibler WB, Uhl TL, Maddux JW, Brooks PV, Zeller B, McMullen J. Qualitative clinical evaluation of scapular dysfunction: a reliability study. J Shoulder Elbow Surg. 2002 Nov-Dec;11(6):550-6.

42. 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 Feb;91(2):378-89.

43. Paletta GA Jr, Warner JJ, Warren RF, Deutsch A, Altchek DW. Shoulder kinematics with two-plane x-ray evaluation in patients with anterior instability or rotator cuff tearing. J Shoulder Elbow Surg. 1997 Nov-Dec;6(6):516-27.

44. Kibler WB, McMullen J. Scapular dyskinesis and its relation to shoulder pain. J Am Acad Orthop Surg. 2003 Mar-Apr;11(2):142-51.

45. Bagg SD, Forrest WJ. A biomechanical analysis of scapular rotation during arm abduction in the scapular plane. Am J Phys Med Rehabil. 1988 Dec;67(6):238-45.

46. 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 Dec;48(8):1503-10.

47. McQuade KJ, Hwa Wei S, Smidt GL. Effects of local muscle fatigue on three-dimensional scapulohumeral rhythm. Clin Biomech (Bristol, Avon). 1995 Apr;10(3):144-148.

48. Braman JP, Engel SC, Laprade RF, Ludewig PM. In vivo assessment of scapulohumeral rhythm during unconstrained overhead reaching in asymptomatic subjects. J Shoulder Elbow Surg. 2009 Nov-Dec;18(6):960-7. Epub 2009 Apr 22.

49. Dayanidhi S, Orlin M, Kozin S, Duff S, Karduna A. Scapular kinematics during humeral elevation in adults and children. Clin Biomech (Bristol, Avon). 2005 Jul;20(6):600-6.

50. Doody SG, Freedman L, Waterland JC. Shoulder movements during abduction in the scapular plane. Arch Phys Med Rehabil. 1970 Oct;51(10):595-604.

51. Michiels I, Grevenstein J. Kinematics of shoulder abduction in the scapular plane. On the influence of abduction velocity and external load. Clin Biomech (Bristol, Avon). 1995 Apr;10(3):137-143.

52. Yano Y, Hamada J, Tamai K, Yoshizaki K, Sahara R, Fujiwara T, Nohara Y. Different scapular kinematics in healthy subjects during arm elevation and lowering: glenohumeral and scapulothoracic patterns. J Shoulder Elbow Surg. 2010 Mar;19(2):209-15. Epub 2009 Dec 7.

53. Hawkins RJ, Angelo RL. Glenohumeral osteoarthrosis. A late complication of the Putti-Platt repair. J Bone Joint Surg Am. 1990 Sep;72(8):1193-7.

54. Garner BA, Pandy MG. Musculoskeletal model of the upper limb based on the visible human male dataset. Comput Methods Biomech Biomed Engin. 2001 Feb;4(2):93-126.

55. Holzbaur KR, Murray WM, Delp SL. A model of the upper extremity for simulating musculoskeletal surgery and analyzing neuromuscular control. Ann Biomed Eng. 2005 Jun;33(6):829-40.

56. van der Helm FC. A finite element musculoskeletal model of the shoulder mechanism. J Biomech. 1994 May;27(5):551-69.