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The effects of arm elevation on the 3-dimensional acromiohumeral distance: a biplane fluoroscopy study with normative data

J. Erik Giphart, PhD, Olivier A.J. van der Meijden, MD, Peter J. Millett, MD, MSc*

Biomechanics Research Department, Steadman Philippon Research Institute, Vail, CO, USA

Hypothesis and background: Narrowing of the subacromial space has been implicated in several shoulder pathologies. However, the location of the minimum distance points during clinical testing has not been defined. We sought to measure the in vivo minimum distance and location of the minimum distance points on the acromion and proximal humerus during arm elevation.
Methods: Eight healthy male subjects (mean age, 30 years) underwent a dynamic in vivo biplane fluoroscopy assessment of scaption and forward elevation. For each frame, the 3-dimensional position and orientation of the humerus and scapula were determined, and the acromiohumeral distance (AHD) was measured as the shortest distance between the acromion and proximal humerus.
Results: The minimum AHD was 2.6 ± 0.8 mm during scaption and 1.8 ± 1.2 mm during forward flexion at elevation angles of 83° ± 13° and 97° ± 23°, respectively. The minimum distance point was located on the articular surface of the humeral head from the neutral arm position until 34° ± 8° for scaption and 36° ± 6° for forward flexion. Upon further elevation, the minimum distance point was located within the footprint of the supraspinatus muscle until 72° ± 12° for scaption and 65° ± 8° for forward flexion. At greater elevation angles, the minimum distance points were between the acromion and the proximal humeral shaft, distal from the greater tuberosity.
Conclusions: The shortest AHD was at approximately 90° of arm elevation. The AHD was no longer measured intra-articularly or within the supraspinatus footprint above approximately 70° of arm elevation.
Level of evidence: Basic Science Study, Anatomic Study, Imaging Normal Subjects.

Keywords: Shoulder; biplane fluoroscopy; subacromial space; kinematics

The subacromial space is important for shoulder joint function. It is confined by the acromial arch superiorly and by the humeral articular surface and greater tuberosity inferiorly. When the subacromial space is narrowed, the distance between the inferior border of the acromion and the proximal humerus, defined as the acromiohumeral distance (AHD), is shortened. The AHD has been reported to be a quantitative measurement that can be used to assess changes in the height of the subacromial space.[9,14-16] Narrowing of the subacromial space has been linked to several shoulder pathologies, including subacromial impingement syndrome and rotator cuff disease.[6,8,13,33] Abduction in the scapular plane and flexion of the shoulder joint have been reported to reduce the AHD, possibly resulting in subacromial impingement.[10,15,16] Several anatomic variations of the acromial arch have been associated with impingement and rotator cuff disease. These

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*Reprint requests: Peter J. Millett, MD, MSc, Steadman Philippon Research Institute, 181 W Meadow Dr, Ste 1000, Vail, CO 81657, USA.

E-mail address: drmillett@steadmanclinic.com (P.J. Millett).

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include a larger lateral extension of the acromion and hooked morphology (type III) of the anterior acromion.[5,34] Clinical examination of the subacromial space is important for the diagnosis of subacromial space pathologies and produces pain during forced upward elevation against the acromion.[19,33] However, the structures being impinged, assuming this is causing the pain, as a function of arm elevation angle during clinical testing have not been well defined.

To better understand and treat shoulder pathology, a precise measurement of shoulder joint kinematics is required. The AHD is certainly influenced by arm position as the various structures, such as the supraspinatus tendon and footprint, rotate beneath the acromial arch. In addition to understanding how arm position affects AHD, normative values are necessary to serve as a reference when clinicians are trying to restore normal kinematics in patients with shoulder pathology, such as rotator cuff repair in patients with rotator cuff tears and subsequent superior migration of the humeral head.

Accurate and precise measurement of glenohumeral kinematics is difficult because the bones of the shoulder complex, especially the scapula, move significantly underneath the skin. Therefore, skin-based measurement techniques cannot measure shoulder joint motion with sufficient accuracy to measure AHD. A highly accurate, emerging tool to measure the in vivo 3-dimensional (3D) kinematics of a joint is biplane fluoroscopy, which eliminates this skin motion artifact by imaging the bones directly. The most accurate measurement method is roentgen stereophotogrammetry analysis,[35] which requires the insertion of small (approximately 1.6-mm) markers inside the bone. Reported accuracies of better than 0.1 mm are possible,[23,36] which make it a suitable reference method for the validation of less invasive techniques.[4,22,24] Model-based techniques, which use bone models reconstructed from computed tomography (CT) or magnetic resonance imaging (MRI), have also been reported to have submillimeter accuracy in measurements of joint kinematics relative to marker-based techniques.[1,4,28]

The purpose of this study was to measure the AHD in vivo during abduction in the scapular plane (scaption) and forward elevation in the sagittal plane to study how arm elevation influenced AHD by use of a biplane fluoroscopy system. Our hypothesis was that the AHD would narrow with increasing arm elevation. In addition, we hypothesized that the location of the minimum distance point on the proximal humerus from which the AHD would be measured would vary with arm position.

Methods

Subjects

For this descriptive laboratory study, 8 healthy male subjects (mean age, 30 ± 7 years; mean height, 1.84 ± 0.05 m; mean weight, 90 ± 9 kg) were recruited. Before participation, all participants signed an informed consent form. Four right shoulders (all dominant side) and four left shoulders (one dominant and three nondominant) were used for analysis. To rule out shoulder pathology, a medical history was taken and full clinical examination of the shoulders was performed. The data collection consisted of (1) a CT scan of the ipsilateral shoulder complex and (2) recording of shoulder motions with a biplane fluoroscopy system.

Procedures

A high-resolution CT scan of each tested shoulder was obtained (Aquilion 64; Toshiba America Medical Systems, Tustin, CA, USA) covering the entire clavicle distally to the inferior angle of the scapula axially and from the spine and sternum to the lateral side of the arm mediolaterally. Axial images of 0.5 mm thickness with a resolution of 512 × 512 pixels (voxel size of approximately 0.7 × 0.7 × 0.5 mm) were acquired by use of clinical shoulder scan technique factors and sharp-bone CT reconstruction. A 3D reconstruction of the bony geometry of the scapula and humerus was then completed by use of commercial software (Mimics; Materialise, Plymouth, MI, USA).

Study participants performed 2 standard range-of-motion exercises inside the biplane fluoroscopy system while seated with their backs straight. The first exercise was shoulder scaption; the arm was held by the side of the body and was then lifted in the scapular plane as far as possible with the thumb pointing upward and elbow fully extended. The second exercise was forward elevation; again, the arm was held by the side of the body, and it was then lifted forward in the frontal plane as far as possible with the thumb pointing upward and elbow fully extended.

The motions were recorded by a biplane fluoroscopy system consisting of 2 BV Pulsera C-arms (Philips Medical Systems, Best, The Netherlands). Using 2 systems with crossed beams allowed true 3D motion reconstructions within the overlapping 3D viewing area. The system was calibrated by imaging a square grid for image distortion correction[11] and a calibration cube to determine the fluoroscopy focus positions (source-to-image distance, 1.5 m) and relative C-arm position and orientation (inter-beam angle, 70°).[23] The control systems of the 2 C-arms were synchronized and operated in automatic pulsed fluoroscopy mode at a frame rate of 30 frames per second (pulse width, 8 milliseconds; 60 mA during pulse; voltage selected by system, approximately 60 kV). The images were extracted and analyzed frame by frame by use of previously reported techniques.[7,12,31,32,39,40]

In summary, after extraction of the 3D geometries of the humerus and scapula from the CT data, a commercial software package (Model-Based RSA; Medis Specials BV, Leiden, The Netherlands),[25] which used a contour-matching algorithm, was used to calculate the 3D bone positions and orientations. Contours were automatically extracted from the fluoroscopy images and manually assigned to each bone for each frame. A fully-automatic 6-*df* contour-matching optimization algorithm determined the 3D bone position and orientation, which optimally matched the detected contours with the projected contours from the imported bone geometries (Fig. 1).

System validation

The biplane fluoroscopy system was validated by standard validation techniques.[4,22,24] Scaption data on 4 cadaveric shoulders

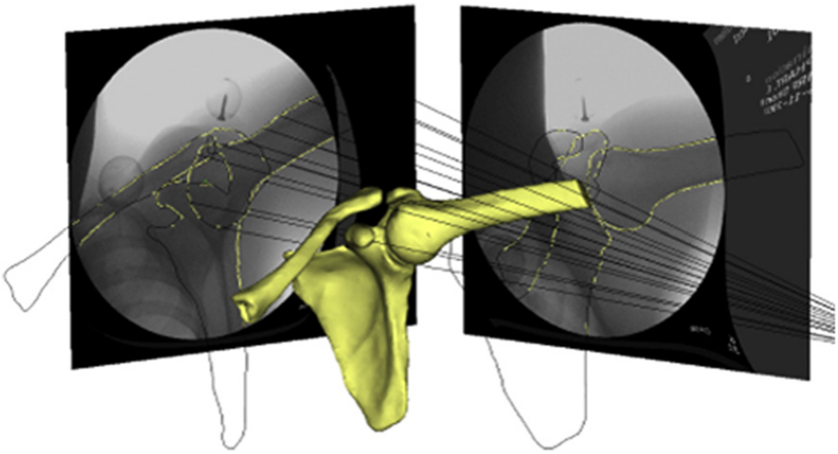

Figure 1 Illustration of data analysis process of scaption frame showing bone reconstructions from CT in 3D reconstructed biplane configuration. The detected contours are shown (*yellow*), as well as the projected contours of the bones (*black*). The bone positions are automatically optimized such that the projected contours optimally match the detected contours in the calibrated images.

were collected in the same manner as in this in vivo study, meaning that the cadaveric shoulders were manually elevated from neutral to maximum elevation in approximately 2 seconds. Thirty frames were used to calculate bias and precision[2] during scaption for each specimen with bead tracking as the reference, and mean bias and precision were 0.2 ± 0.5 mm, 0.3 ± 0.3 mm, and 0.3 ± 0.4 mm for anterior-posterior, superior-inferior, and distraction-compression translations, respectively, and 0.1° ± 0.8°, 0.2° ± 0.2°, and 1.7° ± 1.2° for glenohumeral plane of elevation, elevation angle, and internal rotation–external rotation, respectively. These values were similar to those previously reported for the knee on our system (0.2 ± 0.3 mm, −0.1 ± 0.1 mm, and −0.05 ± 0.1 mm for translations and 0.1° ± 0.1°, 0.3° ± 0.2°, and 0.1° ± 0.3° for rotations)[39] with the exception of internal rotation–external rotation, which is more difficult to measure in the humerus because of its relative cylindrical symmetry. These values are consistent with previously reported studies using similar biplane fluoroscopy technology.[1,4,28]

Data analysis

The AHD was defined as the shortest 3D distance between the acromion and the proximal humerus models and was calculated for every frame of motion by use of custom software (MATLAB; The MathWorks, Natick, MA, USA). The arm elevation angle was defined as the angle between the long axis of the humeral shaft, found by calculating its center line, and vertical and was also recorded for every frame. In addition, the anatomic location of the minimum distance point on the proximal humerus that was used to measure the AHD was recorded for every motion. The minimum AHD and the corresponding arm elevation angle were determined for each motion and each subject. In addition, the AHD was determined for elevation angles starting from 20° to 150° in 10° increments so that the AHD could be averaged across subjects for each elevation angle. Lastly, for each subject, the acromion type[6] and lateral extension[34] were determined from the CT scan.

Statistical methods

A paired *t*-test was used to determine whether the minimum AHD and corresponding arm elevation angle were significantly different between scaption and forward flexion. Acromion types and lateral extension values were correlated with the minimum AHD for scaption and forward flexion by use of Pearson correlations. In addition, a 2-way repeated-measures analysis of variance was performed with independent factors of motion (scaption and forward flexion) and arm elevation angle (20° to 150° in 10° increments). Statistics were determined by use of SPSS software (SPSS, Chicago, IL, USA) with significance set at $P < .05$.

Results

The mean AHD as a function of arm elevation angle for the 2 exercises is shown in Figure 2. The AHD was significantly affected by the plane of elevation ($P = .009$) and by the elevation angle and decreased with arm elevation until a minimum occurred, after which the AHD increased ($P < .0001$). This pattern was consistent among the subjects and exercises. The AHD was significantly higher for scaption compared with forward flexion for arm elevation angles of 120° and 130°. The minimum AHD measured over the range of motion was 2.6 ± 0.8 mm during scaption and 1.8 ± 1.2 mm during forward flexion at elevation angles of 83° ± 13° and 97° ± 23°, respectively (Table I). This difference in minimum AHD between scaption and forward elevation was significant ($P = .002$). The difference between the corresponding angles of elevation was not significant. Three subjects had type I acromions, four had type II acromions, and one had a type III acromion. The lateral acromion index among the subjects was 0.64 ± 0.03. No significant correlations were found between minimum AHD and acromion type and lateral extension.

The path of the minimum distance points between the undersurface of the acromion and the proximal humeral head traveled along the articular surface of the humeral head, the greater tuberosity, and the proximal humeral shaft with increasing elevation. The AHD was measured between the undersurface of the acromion and the articular surface of the humeral head between neutral arm position until

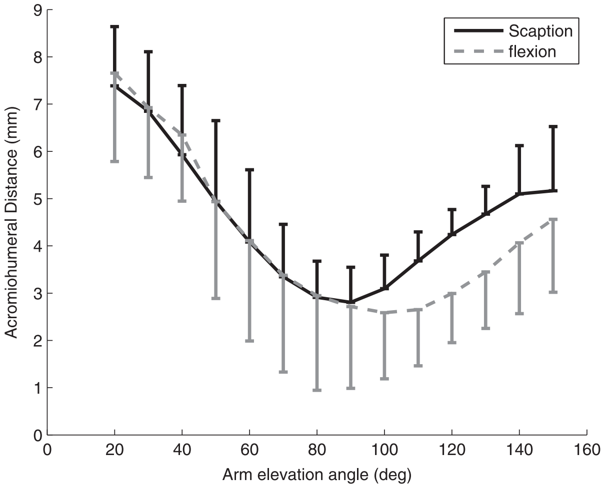

Figure 2 Mean and standard deviation of AHD measured as function of arm elevation angle for scaption and forward flexion.

34° ± 8° of scaption and 36° ± 6° of forward flexion (Fig. 3, *A*). From there, the AHD was measured between the footprint of the supraspinatus on the greater tuberosity and the undersurface of the acromion until 72° ± 12° of scaption and until 65° ± 8° of forward flexion (Fig. 3, *B*). At greater arm elevation angles, the AHD measurement on the humeral side occurred on the humeral shaft outside of the glenohumeral joint (Fig. 3, *C*).

Discussion

We found that the minimum AHD occurred at approximately 90° of arm elevation with minimum distance points at the undersurface of the acromion and the proximal humeral shaft. The minimum distance point was located within the footprint of the supraspinatus on the greater tuberosity between 34° and 72° of scaption and between 36° and 65° of forward elevation. We confirmed our hypothesis that the AHD narrowed during elevation exercises and that the location of the AHD measurement between the undersurface of the acromion and the proximal humerus varied with arm position. We also found that the minimum distance points for clinical testing of subacromial impingement, which is typically performed at approximately 90° of elevation,[19,33] were between the acromion and the proximal humeral shaft and at the approximate minimum AHD distance position.

The clinical relevance of these findings is that they suggest that pain endured during subacromial impingement syndrome is not actually caused by compression of the supraspinatus footprint directly onto the acromion beyond a point of approximately 70° of arm elevation. This brings up the important question of between which structures the impingement occurs, and thus causes the pain, at higher elevation angles. We theorize that our findings could have important clinical implications in the diagnostic evaluation, intraoperative assessment, and postoperative rehabilitation of rotator cuff pathology and other disorders of the subacromial space. For instance, evaluations may be more specific to impingement between the acromion and the supraspinatus tendon and footprint at elevation angles below 70° of elevation. In addition, for elevation angles above shoulder height, the arm should be held in the scapular plane rather than the sagittal plane if impingement is to be minimized, because above 90°, the AHD was less for scaption compared with forward flexion.

The AHD with the arm in neutral position has been previously studied in cadaveric studies using radiographs[10] and in healthy volunteers and patients with impingement syndrome by use of MRI[14-16,18] and ultrasonography.[9,41] The reported mean AHD with the arm in neutral position varied from 7.8 to 12.8 mm.[9,10,38,41] The larger AHD occurred in cadavers[10] and in vivo during the transition from eccentric lowering to raising the arm.[38] The shorter AHD occurred with the arm at rest.[9,41] Our finding of 7.5 mm with the arm at 20° of arm elevation is in agreement with the lower end of the reported AHDs. When the arm is at rest, the long axis of the humeral shaft is at approximately 20° relative to vertical because of the rib cage and the soft tissues between the ribs and the humerus and, thus, corresponds to the neutral arm position.

Previous studies reporting on the AHD as a function of elevation angle report ranges in AHD from approximately 7.0 mm[14,15] at 30° of scaption to 6.7 mm at 60° of scaption[16] during passive movements. Similar to our results, at 90°, the crest of the greater tuberosity has been reported to pass below the acromion at means of 5.4 to 6.7 mm.[10,14,16] Finally, 3.9 mm of AHD has been reported with the upper arm in 120° of scaption.[15] Only one study thus far has reported in vivo 3D AHD with dynamic arm elevation using biplane fluoroscopy technology in older patients who underwent rotator cuff repair.[3] The AHD values ranged from 2.3 to 7.4 mm between 10° and 60° of glenohumeral elevation (15° to 90° of arm elevation), confirming that similar 3D measurements were obtained with similar technology.

With the exception of the findings of Bey et al,[3] the AHDs reported here are shorter than those reported in the literature and our minimum AHD was the smallest AHD reported in healthy subjects. This may be because of several possibilities. It has been documented in the literature that AHD decreases when going from passive to active arm elevation, with narrowing of the subacromial space to as low as 4.1 mm at 60° for loaded scaption.[15,38] In support of this, muscle activation during static poses has been shown to influence AHD.[17,21] In addition, it has been shown that the humeral head is positioned more superior during dynamic motion when compared with static holding of the same elevation angle.[37] A technical reason for the shorter AHD compared with 2-dimensional radiographic studies is that direct measurement of the AHD on radiographic images is affected by magnification. The 3D AHD measure

Table I AHDs measured between undersurface of acromion and various locations of proximal humerus and their corresponding elevation angles for both scaption and forward flexion

	Scaption	Forward flexion
AHD at 20° of arm elevation	7.5 ± 1.2 mm	7.6 ± 1.9 mm
Minimum AHD	2.6 ± 0.8 mm	1.8 ± 1.2 mm
Corresponding angle for minimum AHD	83° ± 13°	97° ± 23°
AHD from rim of articular surface	6.9 ± 1.2 mm	7.1 ± 1.7 mm
Corresponding angle for AHD from rim of articular surface	34° ± 8°	36° ± 6°
AHD from proximal humerus	3.0 ± 0.7 mm	3.5 ± 2.2 mm
Corresponding angle for AHD from proximal humerus	72° ± 12°	65° ± 8°

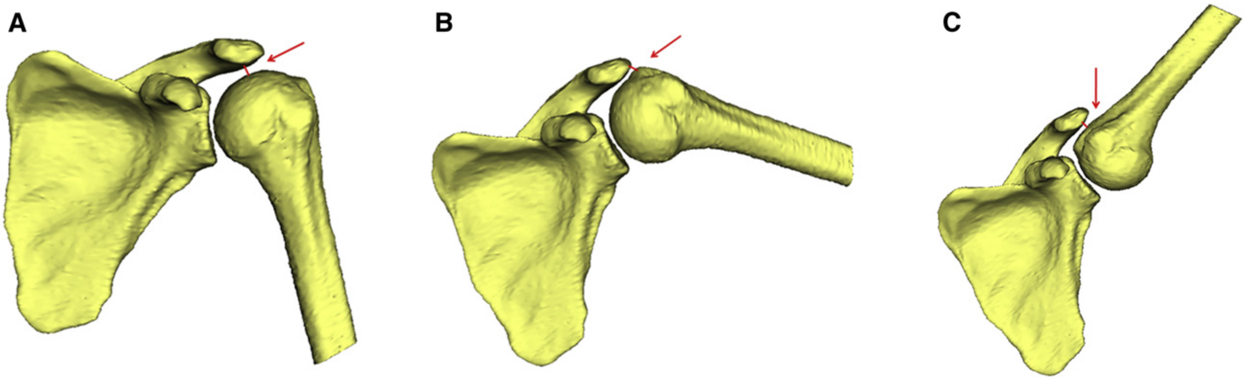

Figure 3 Measurement of AHD (*arrows*) between undersurface of acromion and distal humerus during scaption. At elevation angles below 34° ± 8°, the minimum distance point is located on the articular surface of the humeral head (**A**). Subsequently, the minimum distance point is located on the supraspinatus footprint on the greater tuberosity (**B**) and finally progresses to the proximal humeral shaft at elevation angles greater than 72° ± 12° and is located outside the glenohumeral joint (**C**).

will always be at some distance in front of the image plane, and for a typical setup (source-to-image distance of 100 cm, AHD at 10 cm in front of image plane), this leads to an overestimation of 11%.

Our findings that the footprint of the supraspinatus tendon insertion passed under the acromion at approximately 70° are in concordance with the results of Thompson et al.[38] In addition, it has been theorized that differences in AHD could also be based on the position of the patient during motion exercises (seated, standing, or supine) and gender.[14,38]

It is important to note that in pathologic shoulders, scapular malpositioning (such as kyphosis) and dyskinesia can be important factors influencing AHD. For example, 2 types of abnormalities in scapulohumeral rhythm have been recognized in pathologic shoulders: (1) decreased scapulohumeral rhythm, from increased scapular upward rotation, as a potential compensatory method to potentially increase AHD, avoid impingement symptoms, and improve rotator cuff function[26,30,42,43]; and (2) increased scapulohumeral rhythm, from decreased scapular upward rotation, exacerbating the likelihood of decreased AHD and, thus, impingement.[20,27,29] Biplane fluoroscopy–based techniques measure scapular and humeral position and motion as part of the analysis method and are therefore very well suited to not only detect changes in AHD but also explain how and why AHD is affected by a particular pathology.

Alterations of the AHD in relation to glenohumeral motion have primarily been reported for scaption.[9,14-16,18,38,41] We found that the AHD during forward flexion was smaller at elevation angles greater than 80° compared with the AHD during scaption. A possible explanation for this could be that both exercises were performed with the thumbs up, possibly rotating the greater tuberosity internally during forward flexion and reducing the AHD. Alternatively, we speculate that it is possibly because of the difference in morphology and the amount of coverage by the acromion of the humeral head in relation to the plane of humeral elevation. However, this requires a much more thorough investigation before definite conclusions can be drawn. In addition, impingement with soft tissues rather than bones, such as the coracoacromial ligament, is also a possibility, which cannot be detected with radiography-based techniques.

It is interesting to note that after the minimum AHD, which occurs at approximately 90° of arm elevation, the AHD increased again, as shown in Figure 2. This may be explained by the geometry of the proximal humerus with respect to the center of rotation. As shown schematically in Figure 4, the articular surface of the humeral head is spherical and its center can be reasonably assumed to be the center of rotation. The greater tuberosity deviates from this sphericity and, therefore, reduces the distance to the

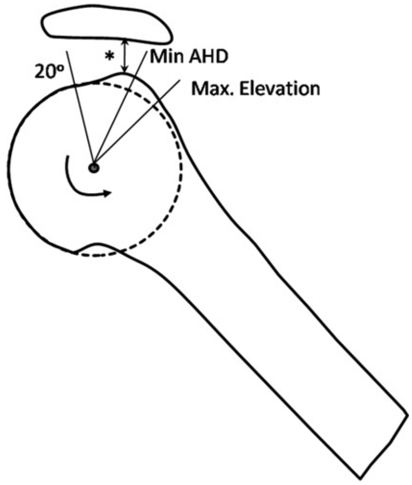

Figure 4 Schema of effect of greater tuberosity on AHD (*asterisk*). As the humerus elevates relative to the scapula, the point location of the AHD travels from the articular surface (20°) over the greater tuberosity (*Min AHD*) onto the proximal humeral shaft (*Max Elevation*). The anatomic distance of the humeral bone surface to the center of rotation varies and coincides with the AHD variations found in this study.

acromion. Once the greater tuberosity has passed under the acromion, the humeral shaft approaches the radius of the sphere and the AHD increases.

A limitation to this study is that radiation was necessary for biplane fluoroscopy measurements. To minimize the amount of radiation as much as possible, caution was taken to use the lowest possible technique factors that still allowed sufficient image quality for motion tracking and a single trial was collected. In the future, MRI rather than CT may be used to obtain bone geometries to further reduce radiation exposure. However, biplane fluoroscopy is presently the most accurate in vivo measurement method that allows the most freedom of movement and highest frame rates. In addition, although using biplane fluoroscopy techniques produces very accurate motions of the bones and direct measures of the AHD, impingement between soft tissues cannot be detected with this technology. Impingement with the coracoacromial ligament could, therefore, not be measured directly in this study. Lastly, the 3D measurements presented in this study require more advanced technologies than the 2-dimensional measurements on clinical radiographs available today and produce shorter AHDs because of the elimination of magnification, projection, and viewing perspective errors. Future studies are necessary to investigate how to obtain more accurate measures of AHD from clinical radiographs.

Conclusion

In vivo normative AHDs were measured in 8 healthy male subjects by biplane fluoroscopy during 2 arm elevation exercises to understand how arm position influenced AHD and to provide reference measures for future studies of shoulder pathology. The minimum AHD measured was 2.6 ± 0.8 mm during scaption and 1.8 ± 1.2 mm during forward flexion at elevation angles of 83° ± 13° and 97° ± 23°, respectively. In addition, the minimum distance points between the acromion and the proximal humerus were documented. The AHD was measured between the undersurface of the acromion and the footprint of the supraspinatus muscle between 34° ± 8° and 72° ± 12° for scaption and between 36° ± 6° and 65° ± 8° for forward flexion. These values may indicate that pain endured during subacromial impingement syndrome is not actually caused by compression of the supraspinatus footprint under the acromion beyond a point of approximately 70° of arm elevation.

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