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A reproducible and practical method for documenting the position of the humeral head center relative to the scapula on standardized plain radiographs

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Background: Recent articles in this journal showed the clinical importance of the position of the humeral head center in relation to the glenoid. However, the precision, reproducibility, and sensitivity of this and other methods of documenting the head center position have not been evaluated in detail.
Materials and methods: We used templates to fit a coordinate system to the scapular anatomy visible on standardized radiographs. Two observers then used these templates to measure the position of the head center relative to this coordinate system on 25 normal shoulder radiographs and on 25 radiographs of shoulders with cuff tear arthropathy (CTA).
Results: Head center measurements had excellent precision. Normal shoulder radiographs showed a consistent head center position (0.7 $\pm$ 1.7 mm medial and 0.6 $\pm$ 1.3 mm inferior to the coordinate origin on the anteroposterior view and 0.1 $\pm$ 1.3 mm medial and 0.0 $\pm$ 1.3 mm anterior to the coordinate origin on the axillary view). The head center of CTA shoulder radiographs was 10.18 $\pm$ 5.16 mm above the coordinate origin on the anteroposterior view, significantly different from that for the normal shoulder radiographs ($P < .001$).
Discussion: The relative position of the humeral head center to the scapula determines the resting length and the moment arms of the scapulohumeral muscles. Correlation of shoulder function with the head center position may provide insights into both shoulder pathomechanics and the optimization of shoulder arthroplasty.
Conclusion: This practical technique showed a high degree of precision and reproducibility for normal and CTA shoulder radiographs as well as a high level of discrimination between these two groups.
Level of evidence: Level IV, Case-Control Study, Diagnostic Study.

Keywords: Glenohumeral joint; humeral head center; validation; reproducibility; radiographs

The position of the humeral head center in relation to the scapula is an important determinant of normal and pathologic glenohumeral mechanics. It represents the center of glenohumeral rotation and helps determine the moment arm and the resting tension of the scapulohumeral muscles. For example, medial displacement of the head center from arthritic glenoid erosion lowers the resting tension of the rotator cuff muscles and reduces the moment arm of the middle deltoid. Superior displacement of the head center from its normal position in rotator cuff tear arthropathy (CTA)

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reduces the resting tension of the deltoid. Although one can gain a qualitative sense of abnormalities in the position of the humeral head center relative to the scapula from inspection of shoulder radiographs, a validated practical, reproducible, and generally applicable method for quantifying the position of the head center relative to the scapula on plain anteroposterior (AP) and axillary radiographs has yet to be established. As shown, most of the previously published reports regarding the documentation of the head center position in relation to the scapula fail to rigorously quantify the intraobserver and interobserver reliability of the measurements; many do not enable the evaluation of the head position in both the AP and axillary projections; and many are not practical in the clinical setting, especially in the situation where metal implants may be in the shoulder, precluding the use of magnetic resonance imaging (MRI) and potentially confounding resolution on computed tomography (Table I). Many of the methods reference the position of the head center to only two points on the scapula, using as a reference the perpendicular bisector of a line drawn from one edge of the glenoid rim to the other as described 33 years ago.[20] Although this method is simple in application, the interobserver and intraobserver reproducibility of this method has not been rigorously examined, and it is not applicable to shoulders in which the glenoid rim has been altered by disease or surgery. Finally, the previously published methods do not scale the measurements to the size of the humeral head so that relative displacements can be compared among shoulders.

Recently, two publications have reported the use of a method for determining the position of the head center relative to the scapula on AP and axillary radiographs to determine the rate of medial migration after hemiarthroplasty with non-prosthetic glenoid arthroplasty[13] and the change in the position of the center of rotation effected by two different types of reverse total shoulder arthroplasty.[23] The method described in these publications fits a coordinate system to the scapular anatomy in the AP and axillary projections of plain radiographs and measures the position of the head center to the origin of the coordinate system. However, the precision, reproducibility, and sensitivity of this method have not been robustly studied previously. The purposes of this study were (1) to describe in detail this method for determining the position of the head center relative to the scapula on scaled plain AP and axillary radiographs, (2) to rigorously quantify the intraobserver and interobserver variability of the method in normal shoulders and in shoulders with rotator CTA, and (3) to show the ability of this method to characterize the head center positions in a group of 25 radiographs of shoulders with CTA in contrast to those in a group of 25 normal shoulder radiographs.

Materials and methods

Approval from the Institutional Review Board at the University of Washington was granted before the review of patient records (No. 24667).

Templates

We designed a pair of transparent templates (Figure 1) that can be superimposed by eye over the lateral scapular radiographic anatomy as seen in the AP view in the plane of the scapula and the true axillary view. The templates establish a scapular coordinate system for documentation of the humeral head center position relative to the scapula.

Radiographs

AP radiographs are taken in a standardized manner with the patient supine and rolled 30° to the side to be imaged with a foam wedge under the opposite side so that the scapula is flat on the radiographic table (Figure 2).[22] The arm is relaxed at the side and externally rotated 30° from the x-ray beam. The axillary radiograph is taken in a standardized manner with the shoulder to be imaged on a foam wedge with the arm relaxed and positioned passively in 90° of abduction and neutrally rotated with respect to the chest. Shoulder radiographs were included in our analyses only if an acceptable pair of an AP view and an axillary view was available for the shoulder on the same date. To enable comparison among shoulders, all radiographs were scaled to a humeral head diameter of 50.8 mm on a picture archiving and communication system (PACS) monitor (GE Healthcare Technologies, Waukesha, WI). This was a commonly represented size in a study of shoulder dimensions.[8] Left shoulder films were flipped to right shoulder views. In the case where a PACS monitor is not available, a similar approach could be used with digital image manipulation software.

Measurements

The transparent AP template was manually superimposed by eye on the scaled PACS image of the scapula on the AP view so that the outline of the glenoid and lateral scapula on the template matched the outline of the glenoid and lateral scapula on the radiograph as closely as possible. The center of the humeral head on the radiographs was determined as the point of two intersecting diameter lines of a circle fit to the humeral head circumference. By use of the coordinate system on the template, the superior/inferior and medial/lateral distances of the radiographic head center from the origin of the coordinate system were measured by use of the PACS toolset. A similar approach was used to measure the AP distance and medial/lateral distance of the radiographic head center from the origin of the coordinate system on the axillary view. Each set of measurements was independently made by two investigators and repeated 7 days later by each of the two investigators. The investigators were blinded to the results of their previous measurements and to the results of the other investigator.

Two sets of radiographs were used in this study. The first consisted of AP and axillary radiographs of 25 shoulders with diagnoses of mild severity that were unlikely to affect the position of the head center, such as bursitis, cuff tendinosis, stiffness, and acromioclavicular joint pain. The patient age averaged 48 years (range, 21-81 years); 12 were female. We refer to these as “normal” shoulder radiographs. The second set consisted of 25 AP and axillary radiographs of shoulders with varying degrees of severity of CTA.[12,16] For the purposes of this study, CTA was defined as an acromiohumeral interval of less than 2 mm on the AP radiograph. The patient age averaged 78 years (range, 66-89 years); 14 were female.

Table I Summary of literature on humeral head center position relative to scapula

Author	Year	In vivo	Imaging	Projection	Scapular reference	Subjects	Reproducibility examined
Poppen and Walker[20]	1976	Yes	Radiography	AP	Bisector of glenoid rim to rim line	Normal and abnormal	No
Howell et al[7]	1988	Yes	Radiography	Ax	Bisector of glenoid rim to rim line	Normal and instability	No
Harryman et al[6]	1990	No	Position Sensor	Ax	Regression		No
Iannotti et al[8]	1992	Yes	MRI	3D	None	Impingement	No
Deutsch et al[4]	1996	Yes	Radiography	AP	Bisector of glenoid rim to rim line	Normal and impingement	[a]
Meskers et al[14]	1998	Yes	Position Sensor	3D	Regression	Normal	[b]
Paletta et al[18]	1997	Yes	Radiography	AP and Ax	Bisector of glenoid rim to rim line	Normal and cuff tear	[c]
Rhoad et al[21]	1998	Yes	MRI	3D	Reconstruction	Normal	No
Beaulieu et al[1]	1999	Yes	MRI	AP and Ax	Bisector of glenoid rim to rim line	Normal	No
Chen et al[2]	1999	Yes	Radiography	AP	Bisector of glenoid rim to rim line	Normal	No
Yamaguchi et al[28]	2000	Yes	Radiography	AP	Bisector of glenoid rim to rim line	Normal and cuff tear	[d]
Veeger[27]	2000	No	Position Sensor	3D	Regression	Normal	No
Graichen et al[5]	2000	Yes	MRI	3D	Center of mass of glenoid	Normal	No
Stokdijk et al[25]	2000	Yes	Position Sensor	3D	Regression	Normal	[e]
Kelkar et al[11]	2001	No	Stereophotogrammetry	3D	None	—	No
Schiffern et al[24]	2002	Yes	MRI	Ax	Bisector of glenoid rim to rim line	Normal and instability	No
Inui et al[9]	2002	Yes	MRI	3D	Reconstruction	Normal and instability	[f]
van de Sande and Rozing[26]	2006	Yes	Radiography and CT	AP	Acromion	Normal and cuff tear	[g]
Nishinaka et al[17]	2008	Yes	Fluoroscopy	AP	Comparison to CT scan	Normal	No
Nagels et al[15]	2008	No	Radiography	AP	Multiple	Normal	[h]
Keener et al[10]	2009	Yes	Radiography	AP	Bisector of glenoid rim to rim line	Normal and cuff tear	[h]
Cote et al[3]	2009	Yes	Radiography	AP	Bisector of glenoid rim to rim line	Normal	[i]

AX, Axillary lateral; *CT*, computed tomography; *3D*, 3-dimensional.

[a] Presented ranges of differences between repeat measurements. The range of differences is dependent on the size of the sample and thus difficult to compare with other studies.

[b] Valid analysis presenting interobserver and intraobserver standard deviations.

[c] Used κ values to indicate reproducibility of parametric variables. κ Values are only applicable to categorical measurements.

[d] Linear regression coefficient used to indicate reproducibility. This is not a standard test of reproducibility.

[e] Attempted to prove reproducibility by comparison of means between the repeated measurements. This is not a standard test of reproducibility.

[f] Presented ranges of differences between repeat measurements. The range of differences is dependent on the size of the sample and thus difficult to compare with other studies. Correlation used to indicate reproducibility. This is not a standard test of reproducibility.

[g] No reproducibility results.

[h] Valid analysis involving interclass correlation coefficients. Limited utility to planning future studies where an absolute measure of accuracy is needed.

[i] No numerical results on reproducibility presented.

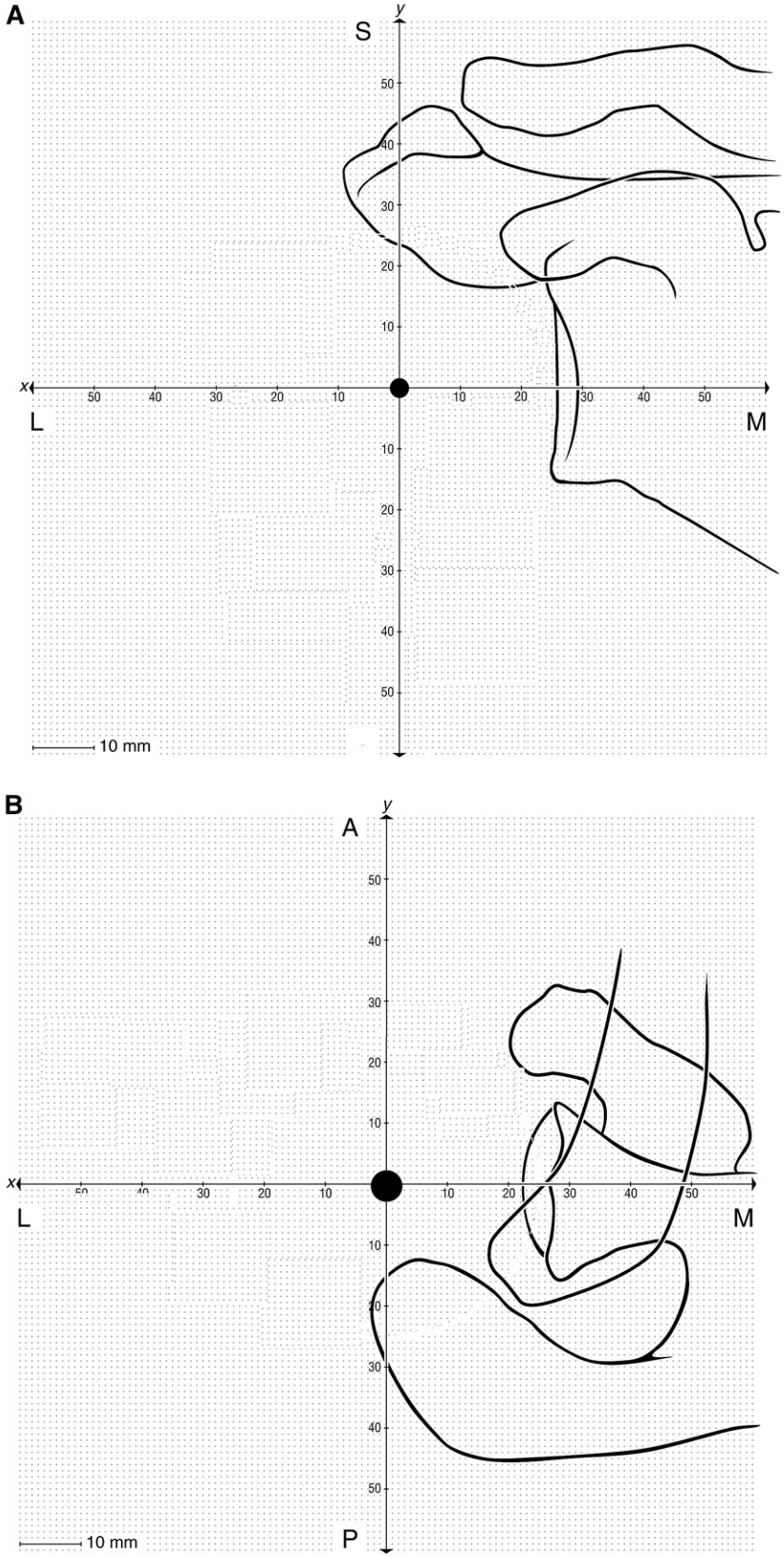

Figure 1 Templates for superimposing a reference coordinate system on radiographic anatomy of scapula: (**A**) AP radiograph and (**B**) axillary radiograph. The transparent template is superimposed on the PACS image of the radiograph scaled to a humeral head diameter of 50.8 mm. The position of the head center is then measured in relation to the origin of the coordinate system (*black circle*).

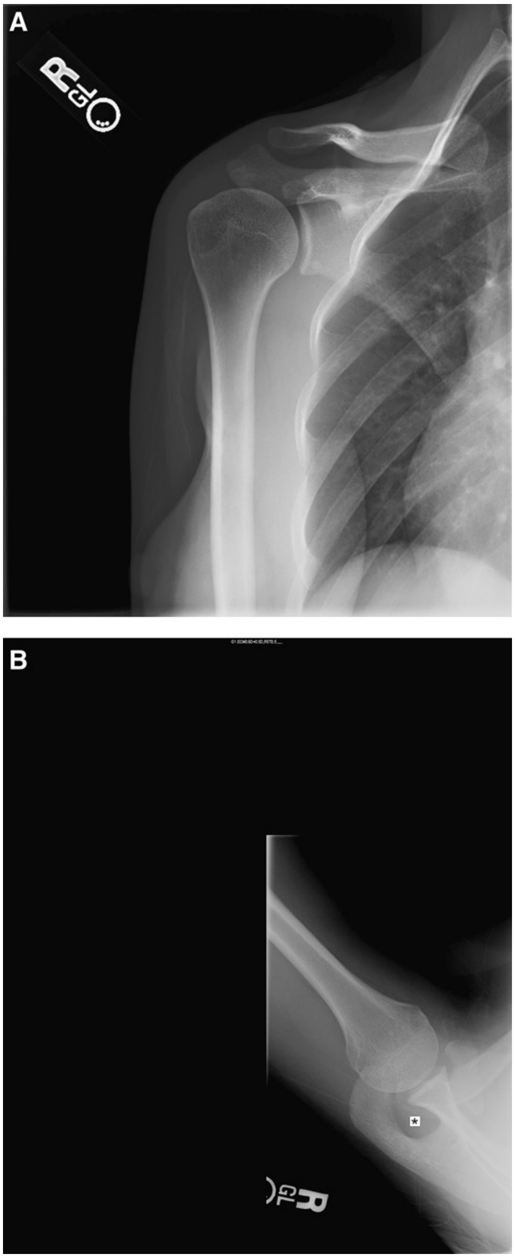

Figure 2 (**A**) AP and (**B**) axillary lateral radiographs of a normal shoulder representing standard radiographic technique. The *asterisk* marks the "eye" of the spinoglenoid notch.

Analysis

Variance components models fitted with restricted maximum likelihood were used to estimate the reproducibility, the between-shoulder variation, and the mean positions for normal and CTA shoulders.[19] The reproducibility results included the intraobserver and interobserver standard deviations (SD_w and SD_b, respectively) and the pooled interobserver and intraobserver standard deviation (SD_r), calculated as $SD_r = \sqrt{(SD_b^2 + SD_w^2)}$. Normal quantile-quantile plots were used to detect outlier shoulders that had large values of intraobserver or interobserver error. Measurements for shoulders with large intraobserver or interobserver error were investigated for possible problems that led to the large measurement error.

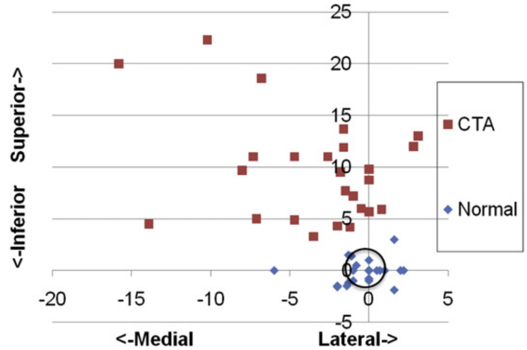

Figure 3 Medial/lateral and superior/inferior head center positions for 25 normal shoulders and 25 shoulders with CTA relative to origin of coordinate system (*circle*) in AP view. Note the clustering of the normal head centers around the origin and the variable but consistently superior displacement of the head centers in shoulders with CTA.

The mean position of the head centers relative to the template coordinate system origin was characterized as the bias (B) and the between-shoulder standard deviation (SD_s). Both B and SD_s were estimated from the variance components model described previously. We anticipated that, for normal shoulders, B would be close to 0 and SD_s would be small. The *P* value for comparing the intercept with 0 in the variance components model was used to compare B with 0. Total standard deviation was defined as $SD_t = \sqrt{(SD_r^2 + SD_s^2)}$. The variance components models were also used to estimate B and SD_s for shoulders with CTA. Estimates of B were compared between normal shoulders and shoulders with CTA by use of the Wald test. All statistical analyses were implemented in R statistical software (Vienna, Austria), version 2.8.0. $P < .05$ was used to designate statistical significance (R Foundation for Statistical Computing; www.r-project.org).

Results

Normal shoulders

Graphical representations of the position of the head center relative to the scapular coordinate system for the radiographs of normal shoulders are shown in Figure 3, which shows the individual data points for the AP projection, and in Figure 4, which shows the mean ± standard deviation of the position in both the AP and axillary projections. The between-shoulder standard deviation was less than 1 mm for the normal shoulders, indicating a high degree of consistency of the relative position of the head center across the normal shoulders. For the 25 normal shoulder radiographs, the mean relative position of the head center was within 0.7 mm of the origin of the coordinate system in both radiographic projections (Table II).

The overall measurement error, expressed by the pooled interobserver and intraobserver SD_r, suggests excellent reproducibility of the position measurements on the normal

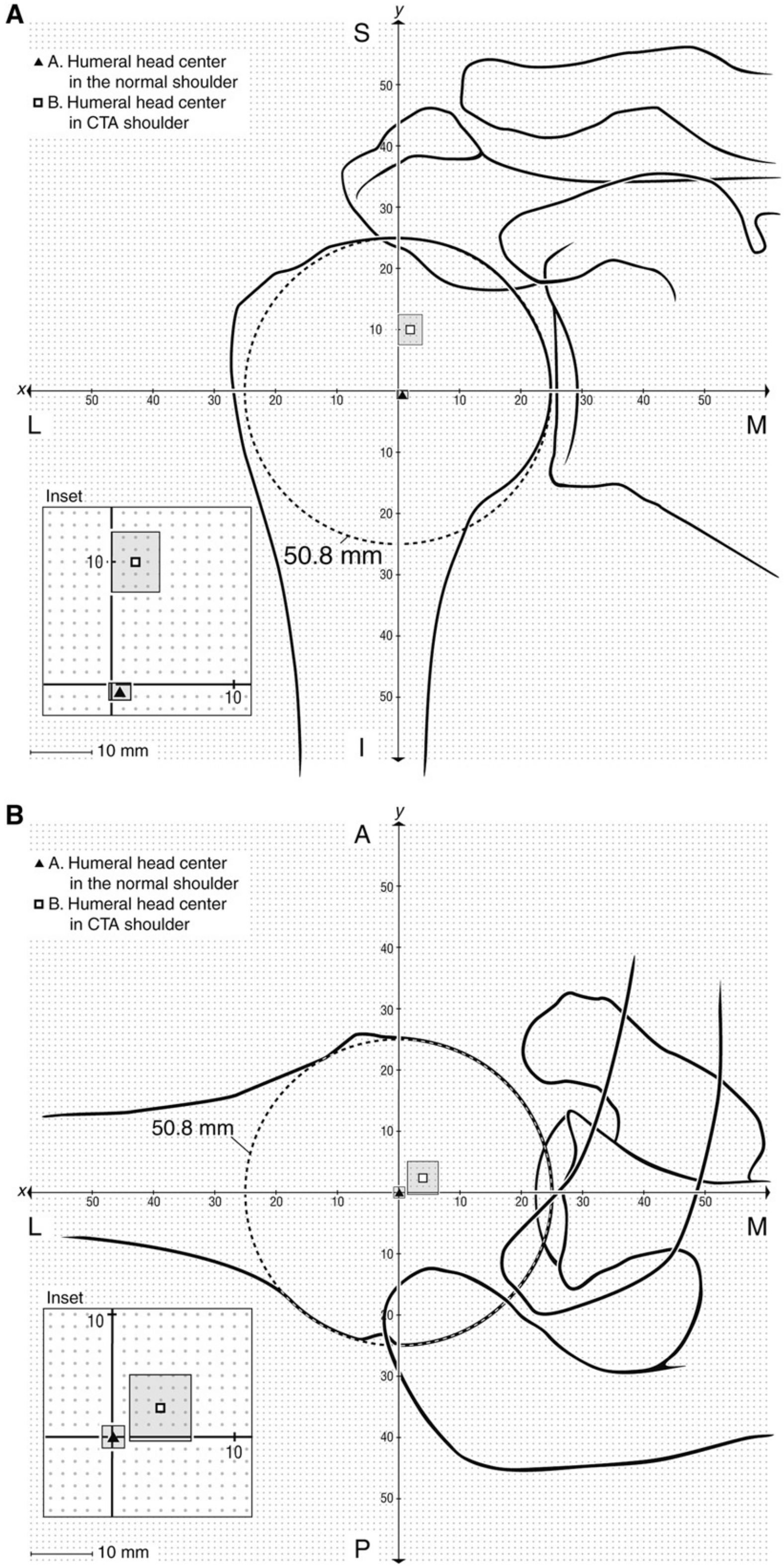

Figure 4 Mean position for head centers of normal shoulders (*black triangle*) and of shoulders with CTA (*white square*) in relation to scapular coordinate system: (**A**) AP view and (**B**) axillary lateral view. The *gray squares* indicate the standard deviations for these measurements. *Insets* show the results with greater magnification.

Table II Reproducibility parameters (25 normal shoulders and 25 CTA shoulders)

Position (view)	Group	Mean position B (*P*)	Between-shoulder SD (SD_s)	Interobserver SD (SD_b)	Intraobserver SD (SD_w)	Pooled interobserver and intraobserver SD (SD_r)	Total SD (SD_t)
Medial/lateral (AX)	Normal	0.13 mm medial (.4)	0.44	0.00	1.27	1.27	1.34
Medial/lateral (AP)	Normal	0.68 mm lateral (.2)	0.60	0.73	1.38	1.56	1.67
Anterior/posterior (AX)	Normal	0.02 mm posterior (>.99)	0.00	0.92	0.98	1.34	1.34
Superior/inferior (AP)	Normal	0.57 mm inferior (.14)	0.00	0.82	0.95	1.26	1.26
Medial/lateral (AP)	CTA	2.28 mm medial (.2)	4.20	2.48	1.03	2.68	4.98
Anterior/posterior (AX)	CTA	1.62 mm anterior (.2)	4.52	1.95	1.07	2.22	5.03
Superior/inferior (AP)	CTA	10.18 mm superior (<.001)	5.16	2.33	1.37	2.70	5.83

$SD_r = \sqrt{(SD_b^2 + SD_w^2)}$ and $SD_t = \sqrt{(SD_r^2 + SD_s^2)}$. Estimates and *P* values based on a variance components model. *P* values are for the comparison of B to 0. *AX*, Axillary lateral.

shoulder radiographs. SD_r describes a typical difference (in millimeters) by which measurements of the same normal shoulder would differ if they were measured once by two different observers. Values of SD_r ranged from 1.26 mm (superior/inferior position) to 1.56 mm (AP radiograph medial/lateral position). For most position parameters, the largest source of measurement error for normal shoulders was intraobserver measurement error (53%-100% of pooled variance SD_r^2). The intraobserver SD for normal shoulders was largest for the AP radiograph medial/lateral position (SD_w, 1.38 mm) and lowest for the superior/inferior position (SD_w, 0.95 mm). The interobserver measurement error for normal shoulders was largest for the AP position (SD_b, 0.92 mm) and lowest for the axillary radiograph medial/lateral position (SD_b, 0.00 mm).

CTA shoulders

Among the four position measurements, two positions exhibited significant differences in the mean relative positions between the 25 CTA shoulders and the 25 normal shoulders: the medial/lateral position on axillary radiographs (3.8 mm medial vs 0.1 mm medial, $P < .001$) and the superior/inferior position (10.2 mm superior vs 0.6 mm inferior, $P < .001$) (Table II and Figures 3 and 4). Individual shoulder measurements on the AP radiograph showed discrimination between the 25 normal shoulders and the 25 CTA shoulders in the inferior-superior direction: no CTA shoulder had a position less than 3 mm superior to the origin, whereas no normal shoulder had a position greater than 3 mm superior to the origin (Table II).

Because of the variability in pathologic anatomy, the measurement error for CTA shoulders was substantially larger compared with the normal shoulder radiographs. The between-shoulder standard deviation was much larger (4-5 mm) in the group of shoulders with varying severities of CTA compared with normal shoulders (<0.7 mm). The pooled interobserver and intraobserver SD was 66% to 114% larger for the CTA shoulders than for the normal radiographs. The measurement of the superior/inferior position had the largest SD_r (2.70 mm). The largest source of measurement error for CTA shoulders was interobserver measurement error (72%-93% of pooled variance SD_r^2). The interobserver SD for CTA shoulders was largest for the medial/lateral position measured on the AP radiograph (SD_b, 2.48 mm). The intraobserver measurement error was largest for the superior/inferior position (SD_w, 1.37 mm).

Outlier detection

Large disagreement in measurement was seen only on poor-quality radiographs and on radiographs where the shoulder anatomy was severely distorted, for example, in the presence of severe medial erosion. There were 4 outliers (0-1 outlier per radiographic parameter) in the normal shoulder group and 8 (0-2 outliers per radiographic parameter) in the CTA shoulder group.

Because the outliers were characterized by large but not extreme disagreements, they were retained in all analyses.

Discussion

Documentation of the position of the head center relative to the scapula is of importance in understanding the effects of pathologic conditions and reconstructive surgery on shoulder mechanics. Our study is unique in that it presents a practical method for this documentation and rigorously investigates the method's precision in terms of its intraobserver and interobserver variability. In a population of normal shoulders, this method showed a high degree of consistency of the position of the humeral head center in relation to scapular reference coordinates. It also showed a consistent direction and magnitude of humeral head center displacement in a population of shoulders with CTA.

Although a number of studies involving the head center position relative to the scapula have been reported, there is no "gold standard" against which our technique can be compared (Table I). Poppen and Walker,[20] Howell et al,[7] Paletta et al,[18] Deutsch et al,[4] Chen et al,[2] Yamaguchi et al,[28] Keener et al,[10] and Cote et al[3] each described radiographic methods for determining the relationship of the center of the humeral head to the center of a line joining two points on the rim of the glenoid fossa. These investigators did not rigorously examine the reproducibility of the measurements of the head center relative to the scapula and did not discuss the applicability of their method to shoulders in which the anatomy of the glenoid fossa is altered by disease or reconstructive surgery so that the two points may no longer be useful as a reference. Other investigators, such as Harryman et al,[6] Meskers et al,[14] Veeger,[27] and Stokdijk et al,[25] used electromagnetic position sensors to determine the center of rotation, but these methods are not commonly available, their interobserver reproducibility is not well defined, and their accuracy in the presence of metal implants is not known. Iannotti et al,[8] Rhoad et al,[21] Beaulieu et al,[1] Graichen et al,[5] Schiffern et al,[24] and Inui et al[9] used MRI to define the relationship of the head to the glenoid, but this technique is not applicable to studies with metal prostheses in place. Nishinaka et al,[17] van de Sande and Rozing,[26] and Kelkar et al[11] also used methods with limited application to the study of abnormal and post-reconstruction shoulders. Nagels et al[15] performed a cadaveric study of 4 methods for measuring proximal migration of the prosthetic head after shoulder arthroplasty. However, their radiographs were taken of shoulders with the soft tissues removed, so the applicability of this method to shoulders in vivo is unclear.

Two recent articles use the method described here. Saltzman et al[23] used scapular coordinate templates to show highly significant differences in the position of the center of rotation after clinical surgical placement of two different types of reverse total shoulder arthroplasty. One (the Delta Shoulder; DePuy, Warsaw, IN) placed the center of rotation 2 $\pm$ 3 mm inferior and 28 $\pm$ 4 mm medial to the coordinate origin, whereas the other (the Encore Shoulder; Encore Medical, Austin, TX) placed the center 7 $\pm$ 3 mm inferior and 19 $\pm$ 3 mm medial. Mercer et al[13] used the template method to measure the rate of medial migration of the humeral head center after humeral hemiarthroplasty with non-prosthetic glenoid arthroplasty. In their series of 14 shoulders with a minimal follow-up of at least 2 years, the rate of medial migration averaged less that 0.4 mm/y. Whereas the latter study compared the results obtained by 2 examiners, neither of these articles rigorously evaluated interobserver and intraobserver variability.

The results of our study need to be considered in light of certain limitations. The 2 observers in this investigation were part of the same shoulder practice; thus, the standardization of radiographic technique and agreement in measurement may be greater than that seen across the practice spectrum. Second, the observers could not be blinded to the diagnosis of normal shoulder versus CTA. Third, the method requires that the size of the radiographs be scaled to a standard size; this requires a system such as PACS that is available in many but not all medical centers. Fourth, these measurements were not compared with a gold standard; as such, a standard has yet to be established (Table I). Finally, this study did not attempt to correlate the position of the head center with the clinical function of the shoulder.

Despite these limitations, this method has been shown to be both precise and practical. It shows consistency in the position of the head center relative to the scapula on normal shoulder radiographs. It also quantifies the characteristic displacement of the humeral head center in shoulders with CTA, indicating the method's applicability to conditions that deform the glenohumeral joint. Because this method does not use MRI, computed tomography, or electromagnetic sensors, it is also applicable to the assessment of shoulders after arthroplasty, enabling documentation of the change in relative head position before and after reconstruction.

Conclusions

This quantitative method of documenting the position of the humeral head center relative to the scapula appears generally applicable. It can help characterize the pathoanatomy in individual shoulders and cohorts of shoulders as well as the effect of different methods of glenohumeral reconstruction on the position of the humeral head center relative to the scapula.

Disclaimer

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