



A reliable method of determining glenohumeral offset in anatomic total shoulder arthroplasty

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Background: Glenohumeral offset (GHO) may change from the preoperative state after anatomic total shoulder arthroplasty (TSA), and has been identified as a factor that may affect shoulder mechanics, strength, and function. The primary objective was (1) to establish a reliable method of measuring GHO with standardized computed tomography (CT) imaging planes and (2) to determine whether an association exists between GHO and functional outcomes in TSA.

Methods: Thirty-seven patients underwent TSA for glenohumeral osteoarthritis. Preoperative and postoperative CT scans were reformatted along standardized measurement planes for the glenoid and humerus separately. Inter-rater and intrarater reliability was determined for 3 methods to measure humeral offset and 2 methods to measure glenoid offset. Univariate regression analysis was used to determine the association between GHO and functional outcomes including the Constant score and strength.

Results: Of all methods tested, the highest preoperative and postoperative inter-rater reliability was $r = 0.84$ and $r = 0.8$, and $r = 0.7$ and $r = 0.8$ for humeral and glenoid offset, respectively. Intrarater reliability was >0.94 . There was a mean increase of 4.3 mm (standard deviation, 4.6; range, -10.6 to 10.8) in combined GHO from preoperative to postoperative time points. No associations were observed between change in offset and functional or strength scores.

Discussion: A reliable approach to measure prearthroplasty and postarthroplasty GHO with CT plane standardization has been described. A net increase in GHO was observed after TSA. No associations were found between change in offset after TSA and functional scores or strength up to 2 years postoperatively.

Level of evidence: Level IV; Case Series; Treatment Study

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Keywords: Glenohumeral offset; lateral humeral offset; shoulder offset; shoulder arthroplasty

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Anatomic total shoulder arthroplasty (TSA) is used to reliably treat pain due to symptomatic glenohumeral osteoarthritis. As arthritis progresses, volumetric bone loss occurs on the humeral head and glenoid resulting in loss of glenohumeral offset (GHO). This decrease in offset may affect shoulder mechanics by altering deltoid and rotator cuff moment arms as well as the tension of capsular tissue.^{13,15,24,26} However, the association between GHO, postoperative function, and range of motion (ROM) is not well understood,^{6,30} and the preoperative to postoperative change in offset may differ significantly depending on the severity of the arthritis and surgical factors.

Various radiographic methods have been used to measure GHO,^{11,16,17,25} yet reliability and accuracy remain modest due to difficulty in identifying anatomic landmarks and inconsistency of radiographic imaging planes.^{14,18,28,31} Computed tomography (CT) has demonstrated better reliability;^{5,18} however, lack of standardization of the imaging plane has made preoperative to postoperative GHO comparisons challenging, and the correlation between functional outcomes and GHO in TSA has seldom been studied.^{11,18}

Our hypothesis was that glenohumeral joint reconstruction with a third-generation prosthetic humeral head and glenoid replacement with an all-polyethylene component may result in an increase in GHO. The purpose of this study was (1) to establish a reliable method of measuring GHO with standardized CT imaging planes with independent measurement of the glenoid and humeral offset so as to control for the glenohumeral relationship in space, and (2) to determine whether an association exists between GHO and functional outcomes in shoulder arthroplasty.

Materials and methods

Patients included in the study were enrolled in a prospective randomized clinical trial comparing lesser tuberosity osteotomy with subscapularis peel.²¹ Research ethics board approval for this study was obtained. Inclusion criteria included failure of a minimum of 6 months of standard nonsurgical management for osteoarthritis.²¹ The exclusion criteria included active joint or systemic infection, rotator cuff arthropathy, muscle paralysis, neuropathic arthropathy, major medical illness (a life expectancy of less than 1 year or an unacceptably high operative risk), inability to speak or read English or French, psychiatric illness that precluded informed consent, and inability to be followed for 2 years. The surgical approach has been previously described.²¹ All surgical procedures were performed by one of 2 shoulder fellowship-trained surgeons (P.L. and G.S.A.) using press-fit humeral stems and keeled, cemented glenoid components (Aequalis; Tornier, Montbonnot, France). Intraoperatively, patients were randomized to either lesser tuberosity osteotomy or subscapularis peel for management of the subscapularis. Postoperative rehabilitation was standardized with sling immobilization for 6 weeks. Self-assisted forward elevation was initiated on the first postoperative day to a maximum of 90, and self-assisted external rotation was limited to neutral for the first 6 weeks. Active

ROM and physiotherapy were initiated at 6 weeks postoperatively, with gentle strengthening exercises initiated at 12 weeks postoperatively.

CT scans of the operative shoulder were performed preoperatively and 1 year postoperatively. One patient died before the 6-month follow-up, and therefore no postoperative CT imaging was available. The study cohort therefore consisted of 37 patients with osteoarthritis (14 male; 23 female) with a mean age of 68 (standard deviation [SD], 11; range, 34-90) years. Surgery was carried out on the dominant arm in 20 patients (54%). Seventeen patients underwent a lesser tuberosity osteotomy, and 20 underwent a subscapularis peel. There was 100% healing in both lesser tuberosity osteotomy and peel cases in this series at 12 months postoperatively.²² The mean preoperative Goutallier fatty infiltration index¹⁰ was 0.72 (SD, 0.79); glenoid morphology Walch classification¹ was as follows: A1, 10.8%; A2, 51.4%; B1, 8.1%; B2, 16.2%; B3, 10.8%; D, 2.7%. Demographic variables are summarized in Table I.

Outcome variables

CT plane standardization

To mitigate differences in patient position and imaging planes, CT planes were realigned in a standardized fashion. Humeral and glenoid offset were determined independently to control for arm position. For humeral offset measurements, CT planes were realigned based on humeral landmarks; for glenoid offset, CT planes were realigned based on scapular landmarks. CT imaging planes for the humerus and scapula were standardized across the axial and coronal planes. Reproducible landmarks outside the areas subjected to surgical reconstruction were identified on the scapula and humerus. Analyses were carried out using a Toshiba Medical Vitrea Workstation (Canon Medical Systems, Ōtawara, Tochigi, Japan) with 3-dimensional analysis function.

For humeral offset measurements, images were realigned in the axial plane parallel to a line along the anterior cortex of the humerus 5 cm below the greater tuberosity, and in the sagittal plane parallel to the central axis of the humeral shaft (Fig. 1, A). Coronal plane images along these new standardized axes were used to determine humeral offset corresponding to a slice through the center of the humeral shaft in the sagittal plane (Fig. 1, B). For glenoid offset measurements, the coronal plane was realigned along a line parallel to the inferior cortex of the mid-acromion; the sagittal plane was realigned along a line parallel to the superior cortex of the coracoid (Fig. 2, A). Axial plane reconstructions along these new standardized axes were used for glenoid offset measurements corresponding to a slice through the center of the coracoid and parallel to its superior cortex in the sagittal plane (Fig. 2, B).

Humeral and glenoid offset measurements

Humeral and glenoid offset were adapted from a previously described radiographic method.¹⁷

Three humeral offset measurement approaches were studied (Fig. 3). Method H1 was defined as the perpendicular distance from the long axis of the humeral diaphysis to the most medial aspect of the humeral head. Method H2 was defined as the perpendicular distance from the long axis of the humerus to the middle of the articular surface along the neck/shaft angle. To ensure accuracy, the neck shaft angle (NSA) as measured

Table I Demographic data for included patients (N = 37)

Demographic variable	Data
Age (yr)	67 (10.8)
Gender (male:female)	14:23
Operative side: dominant arm	20 (54%)
Type of repair subscapularis	20 osteotomy/ 17 tenotomy
Mean global fatty infiltration index	0.72 (SD 0.79)
Walch glenoid classification	A1: 10.8% A2: 51.4% B1: 8.1% B2: 16.2% B3: 10.8% D: 2.7%

SD, standard deviation.

preoperatively was used for preoperative and postoperative offset measurements. This angle was measured between a line parallel to the humeral shaft and a second line perpendicular to a line between the superior and inferior aspects of the humeral neck. Method H3 was measured in a similar fashion to Method H2, but with a standardized NSA of 135°. ¹⁶ The distance from the greater tuberosity to the intersection point of the NSA and the long axis of the humerus was standardized at 1.75 cm from pooled study data from method H2 of the current study to improve reliability.

Two glenoid offset methods were tested (Fig. 4) that were referenced on Friedman's line. ⁸ In method G1, the glenoid offset was defined as the perpendicular distance between a line intersecting the lateral base of the coracoid process and a line intersecting the midpoint of the glenoid articular surface. Method G2 was the perpendicular distance between the medial base of the coracoid process and the midpoint of the glenoid articular surface. For biconcave glenoids (Walch B2), ¹ the midpoint of the articular surface was defined as the midpoint of the glenoid facet, on which the humeral head articulated to most accurately represent functional offset.

Combined offset was defined as the sum of humeral and glenoid offset measurements. This combined offset was comparable with previously described "lateral humeral offset." ^{16,17}

Functional outcomes

Functional outcome measures were performed preoperatively and at 24 months postoperatively. These included the Constant-Murley score, subscapularis, and supraspinatus strength testing. The Constant score is a validated assessment of shoulder function based on both subjective findings (severity of pain, activities of daily living) and objective measures (strength and ROM). ^{4,12,27} Subscapularis muscle strength was tested in the belly-press position and measured with an electronic handheld dynamometer. ^{9,23} Supraspinatus strength was measured with a hand-held scale in the scaption position at 90° flexion with the mean of 3 trials of maximal effort.

To determine interobserver reliability, all CT plane standardization and offset measurements were performed by 2 different assessors (A.B., L.H.). Each assessor realigned the CT images, chose the appropriate image slice, and performed all

measurements independently of one another. Intrarater reliability was determined by repeating the measurements after a 2-week interval.

Statistical methods

The mean, standard deviation, and range were reported for the outcome variables as well as offset measurements. Two-way intraclass correlation coefficients were calculated to determine the inter-rater and intrarater reliabilities of the offset measurement techniques. Pearson correlation coefficients were calculated using the most reliable offset measurement techniques to determine associations between preoperative offset parameters and functional outcomes, and postoperative offset parameters and functional outcomes. Linear univariate regression analysis was used to determine association between functional outcomes and preoperative to postoperative offset change. Statistical significance was set at $P < .05$.

Results

Of the 3 methods of measuring humeral offset, method H1 demonstrated the highest interobserver reliability with preoperative CT at 0.84 (95% confidence interval [CI]: 0.71, 0.91) and postoperative CT at 0.81 (95% CI: 0.67, 0.89) (Table II). Method G2 for glenoid offset was found to have the highest interobserver reliability with values of 0.70 (95% CI: 0.51, 0.83) preoperatively and 0.80 (95% CI: 0.64, 0.88) postoperatively. All intrarater reliabilities were greater than 0.85.

Offset measurements

Overall, there was an increase in mean offset from the preoperative to the postoperative state for the humerus of 1.7 mm (SD, 2.5 mm) and the glenoid (2.6 mm; SD, 3.2 mm) for a combined mean increase in offset of 4.3 mm (SD, 4.6 mm) (Table III). Combined offset was restored to within 10 mm of the preoperative offset in 34 of 37 patients (92%), whereas 17 of 37 patients (46%) were restored to within 5 mm.

Correlation between offset measurements and functional outcomes

The "estimate" is a determination of association between the preoperative and postoperative change in offset, as well as the change in functional score from baseline to 2 years postoperatively (Table IV). For example, a 1 mm increase in humeral offset was associated with a 1.6 increase in the Constant score from baseline to 2 years. No associations were statistically significant; however, the change in the Constant score was not correlated with the change in humeral offset ($P = .1771$), glenoid offset ($P = .1697$), or combined offset ($P = .0902$). Similarly, no significant

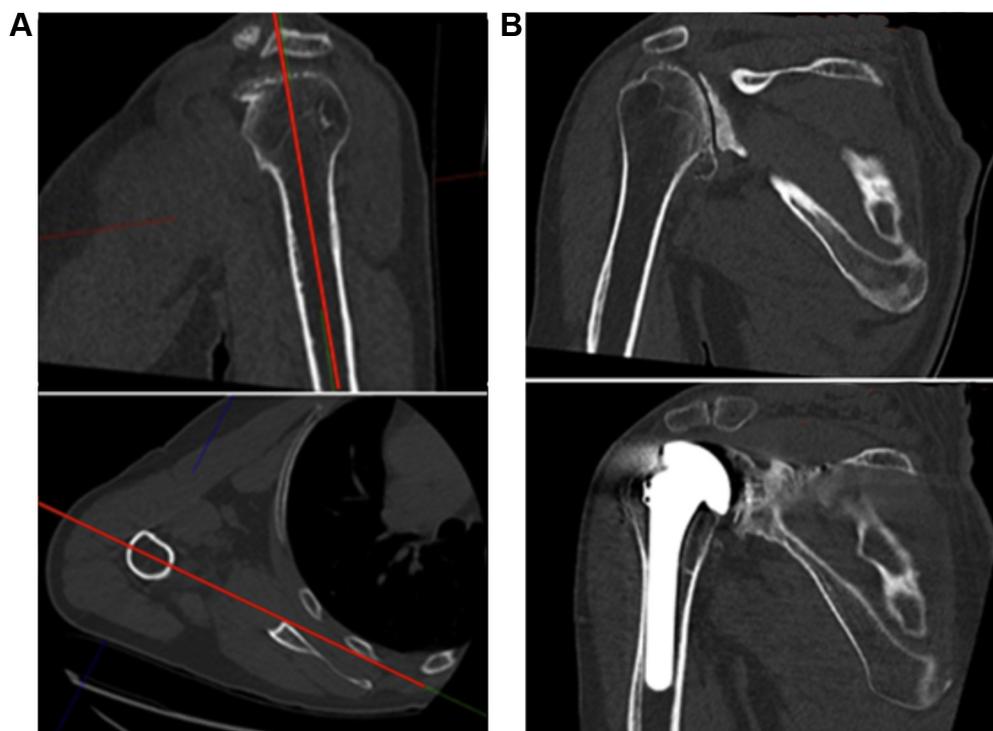


Figure 1 (A) Adjusting the sagittal plane in line with the central axis of the humeral shaft (red line, upper image) and the axial plane in line with the anterior cortex of the humerus 5 cm below the greater tuberosity (red line, lower image) produced standardized coronal plane cuts of the humerus. (B) The coronal plane cuts were then used for offset measurements.

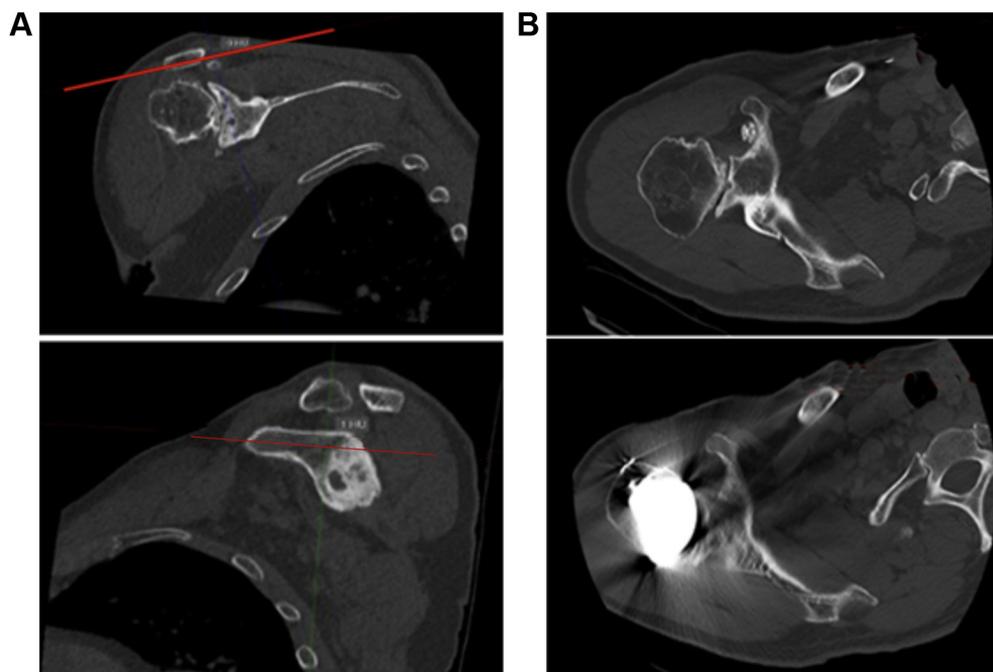


Figure 2 (A) Adjusting the coronal plane in line with the inferior cortex of the acromion (red line, upper image) and the sagittal plane in line with the superior cortex of the coracoid (red line, lower image) produced standardized axial plane cuts of the glenoid. (B) The axial plane cuts were then used for offset measurements.



Figure 3 Humeral offset measurements. (A) Method H1: middle of the humeral shaft to the medial-most aspect of the humeral head (red line), (B) method H2: middle of the humeral shaft to the medial humeral head along the neck shaft angle (red line), and (C) method H3: middle of the humeral shaft to the medial humeral head along the neck shaft angle of 135° (red line).

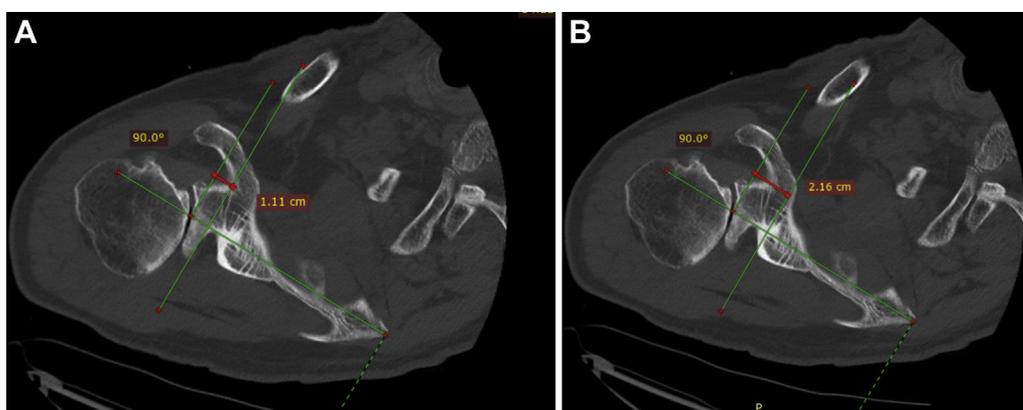


Figure 4 Glenoid offset measurements. (A) method G1: base of the lateral coracoid to the midarticular glenoid (red line), and (B) method G2: medial base of the coracoid to the midarticular glenoid (red line).

associations were observed between the change in humeral, glenoid, or combined offset and the change subscapularis strength or supraspinatus strength ($P > .05$). This lack of apparent association is seen in [Figure 5](#).

Discussion

The most reliable method to determine humeral offset was method H1: the perpendicular distance from the long axis of the humeral diaphysis to the most medial aspect of the humeral head. The perpendicular distance between the medial base of the coracoid process and the midpoint of the glenoid articular surface yielded the most reliable results for determination of glenoid offset. Interobserver and intraobserver reliability of measurements was high, and this allowed preoperative scans and postoperative scans to be compared. No associations were observed between the change in GHO and functional outcome measure preoperatively to postoperatively.

Osteoarthritis of the glenohumeral joint is characterized by humeral and glenoid volumetric bone loss resulting in

medialization of the joint line. Our data indicated that offset increased with insertion of prosthetic shoulder components from the preoperative to postoperative state, on both humeral and glenoid sides, with a mean combined increase of 4.7 mm. This increase was due to relatively equivalent increases in offset on both the humeral and glenoid sides (see [Table III](#)).

Factors associated with postoperative ROM after TSA include preoperative diagnosis, preoperative ROM, preoperative state of soft tissues, joint stability, intraoperative ROM, and rehabilitation.^{3,7,20,29} GHO has the potential to influence ROM due to its effect on deltoid and rotator cuff moment arms as well as capsular tensioning,^{13,15,24,26} although this association has not been previously observed in vivo in anatomic TSA.^{11,19} Previous studies have relied on plain radiographs, which may be unreliable due to difficulty in identifying anatomic landmarks, varying angles of the radiographic beam, and varying 3-dimensional positioning of the glenohumeral joint.^{2,18,28,31} CT scan methods have demonstrated significantly higher reliability,^{5,18} and CT plane standardization is necessary to allow for preoperative to postoperative comparison.

Table II Inter-rater and intrarater reliability for offset measurement methods (ICC values)

Offset measurement method	Preoperative	Postoperative
Humeral method H1	0.84 (0.71, 0.91)	0.81 (0.67, 0.89)
Humeral method H2	0.60 (0.39, 0.78)	0.45 (0.23, 0.70)
Humeral method H3	0.78 (0.63, 0.88)	0.79 (0.64, 0.88)
Glenoid method G1	0.54 (0.31, 0.74)	0.73 (0.55, 0.85)
Glenoid method G2	0.70 (0.51, 0.83)	0.80 (0.64, 0.88)
Intrarater reliability	0.94	0.98

ICC, Intraclass correlation coefficient.

Table III Descriptive statistics for humeral offset method 1 and glenoid offset method 2: radiologic parameters

Humeral offset: method H1 (mm)	Mean (SD)	Minimum	Maximum
Preoperative	27.3 (2.7)	23.4	32.7
Postoperative	28.9 (3.2)	23.5	35.4
Glenoid offset method G2 (mm)			
Preoperative	20.8 (5.3)	9.7	30.3
Postoperative	23.4 (6.4)	10.2	36.4
Combined offset (mm)			
Preoperative	48.1 (6.5)	35.5	60.3
Postoperative	52.37 (7.9)	34.2	64.6
Change in offset (mm)			
Humeral	1.7 (2.5)	-4.8	6.3
Glenoid	2.6 (3.2)	-8.0	6.9
Combined	4.3 (4.6)	-10.6	10.8

SD, standard deviation.

Table IV Associations between the change in offset and functional outcomes

Variable	Estimate	P value
Change in Constant score (baseline to 2 yr)		
Change in humeral offset	1.60501309	.1771
Change in glenoid offset	1.24803012	.1697
Change in combined offset	1.06916277	.0902
Change in SSC strength (baseline to 2 yr)		
Change in humeral offset	-0.070177348	.5611
Change in glenoid offset	-0.144905001	.1106
Change in combined offset	-0.090919893	.1538
Change SSP strength (baseline to 2 yr)		
Change in humeral offset	0.361708943	.3291
Change in glenoid offset	0.345968284	.2203
Change in combined offset	0.272589933	.1659

SSC, subscapularis; SSP, supraspinatus.

The H1 and G2 approaches were adapted from a previous approach using plain radiographs.¹⁶ In the current study, humeral and glenoid offset were measured independently and combined to eliminate variability in arm position on imaging. The center of the humeral shaft was used for humeral offset measurement as described by Jacobson and Mallon.¹⁷ This provided a definable

reference point comparable with postoperative CT. Humeral center of rotation measurements were avoided as these values were not reliable due to loss of humeral head sphericity. Friedman's line was used for glenoid offset measurement as it remained constant from the preoperative to postoperative state and is independent of glenoid version.

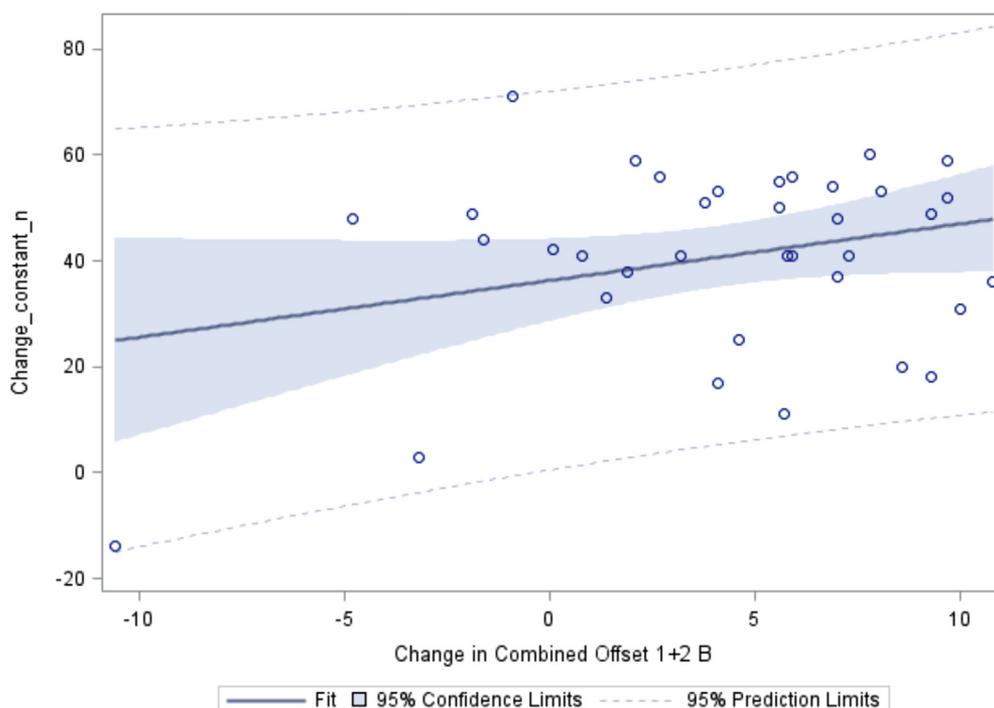


Figure 5 Exploratory plot of the association between preoperative and postoperative change in combined offset and preoperative to postoperative change in the Constant score. The plot demonstrates that no association is apparent.

Previously described methods were primarily developed in nonarthritic shoulders,^{16,17,25} and therefore, reliability of these measurements in arthritic and postoperative shoulders cannot be discerned. The current method demonstrated strong inter-rater reliability values in end-stage arthritic shoulders on preoperative images. Postoperative inter-rater reliability values were moderate despite metal artefact. Previous studies have shown excellent interobserver and intraobserver reliability in measuring lateral GHO with Intraclass correlation coefficient (ICC) values greater than 0.9.^{5,18} However, CT scan plane standardization was not performed in either of these studies.

No associations between the change in GHO and functional outcomes were observed including the Constant score, subscapularis strength, and supraspinatus strength. Two previous studies, one using radiographs and the other using CT scans, similarly found no correlation between GHO and functional outcomes.^{10,11,17,18} It is possible that the outcome metrics did not have the sensitivity to detect functional differences across the relatively small changes in offset observed in the current study. These findings are reassuring that anatomic reconstruction with lateralization of the joint line and restoration of humeral head sphericity did not compromise shoulder function or strength within the range of offset change observed in the study. Although we were not able to test this hypothesis in the current study, there is likely an inflection point in the offset/strength curve past which increasing offset becomes detrimental. Stretching the capsule and tendons beyond their normal

length may result in a decline in contractility with effects on subscapularis healing rates and possibly adverse consequences on prosthetic survivorship due to increased joint reaction forces.

This study had certain limitations including low patient numbers that may have limited the identification of associations between offset and function. However, plots were generated to determine the degree of association between offset and function, and no such association was observed, which appears to indicate that no true association exists. It is possible that current functional scores may lack the sensitivity to discern small differences in function. Postoperative CT scan measurements are limited by metal artefact, although all CT scans were performed using metal artefact reduction sequences and all bony landmarks were readily identifiable.

Conclusions

CT plane standardization and independent measurement of humeral and glenoid offset was a reliable approach to determination of lateral GHO in patients undergoing TSA. TSA resulted in a net increase in GHO. Future studies may use this approach in larger cohorts to define the optimal degree of offset in glenohumeral arthroplasty and its correlation with functional or radiographic outcomes.

Disclaimer

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