Implant-Positioning and Patient Factors Associated with Acromial and Scapular Spine Fractures After Reverse Shoulder Arthroplasty

A Study by the ASES Complications of RSA Multicenter Research Group

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Background: This study aimed to identify implant positioning parameters and patient factors contributing to acromial stress fractures (ASFs) and scapular spine stress fractures (SSFs) following reverse shoulder arthroplasty (RSA).

Methods: In a multicenter retrospective study, the cases of patients who underwent RSA from June 2013 to May 2019 and had a minimum 3-month follow-up were reviewed. The study involved 24 surgeons, from 15 U.S. institutions, who were members of the American Shoulder and Elbow Surgeons (ASES). Study parameters were defined through the Delphi method, requiring 75% agreement among surgeons for consensus. Multivariable logistic regression identified factors linked to ASFs and SSFs. Radiographic data, including the lateralization shoulder angle (LSA), distalization shoulder angle (DSA), and lateral humeral offset (LHO), were collected in a 2:1 control-to-fracture ratio and analyzed to evaluate their association with ASFs/SSFs.

Results: Among 6,320 patients, the overall stress fracture rate was 3.8% (180 ASFs [2.8%] and 59 SSFs [0.9%]). ASF risk factors included inflammatory arthritis (odds ratio [OR] = 2.29, p < 0.001), a massive rotator cuff tear (OR = 2.05, p = 0.010), osteoporosis (OR = 2.00, p < 0.001), prior shoulder surgery (OR = 1.82, p < 0.001), cuff tear arthropathy (OR = 1.76, p = 0.002), female sex (OR = 1.74, p = 0.003), older age (OR = 1.02, p = 0.018), and greater total glenoid lateral offset (OR = 1.06, p = 0.025). Revision surgery (versus primary surgery) was associated with a reduced ASF risk (OR = 0.38, p = 0.019). SSF risk factors included female sex (OR = 2.45, p = 0.009), rotator cuff disease (OR = 2.36, p = 0.003), osteoporosis (OR = 2.18, p = 0.009), and inflammatory arthritis (OR = 2.04, p = 0.024). Radiographic analysis of propensity score-matched patients showed that a greater increase in the LSA (ΔLSA) from preoperatively to postoperatively (OR = 1.42, p = 0.005) and a greater postoperative LSA (OR = 1.76, p = 0.009) increased stress fracture risk, while increased LHO (OR = 0.74, p = 0.031) reduced it. Distalization (ΔDSA and postoperative DSA) showed no significant association with stress fracture prevalence.

continued

*Members of the ASES Complications of RSA Multicenter Research Group are included as a note at the end of the article.

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Conclusions: Patient factors associated with poor bone density and rotator cuff deficiency appear to be the strongest predictors of ASFs and SSFs after RSA. Final implant positioning, to a lesser degree, may also affect ASF and SSF prevalence in at-risk patients, as increased humeral lateralization was found to be associated with lower fracture rates whereas excessive glenoid-sided and global lateralization were associated with higher fracture rates.

Level of Evidence: Prognostic Level III. See Instructions for Authors for a complete description of levels of evidence.

Reverse shoulder arthroplasty (RSA) has been demonstrated to effectively treat many challenging degenerative conditions around the shoulder[1]. Despite its burgeoning popularity, a growing awareness of certain complications specific to RSA, such as acromial stress fractures (ASFs) and scapular spine stress fractures (SSFs), has developed in the setting of its increased utilization as well as broadened indications[2,3]. While the prevalence of these fractures has been estimated to range between 0.8% and 15%, a recent multicenter study including 6,755 RSA-treated patients reported a more conservative prevalence of 3.9%[4].

Implant designs have varied since the initial Grammont prosthesis, with contemporary designs producing greater amounts of glenoid lateralization, various neck-shaft angles, and variable humeral-sided lateralization in order to increase the resting muscle tension of the deltoid and available rotator cuff[5]. Furthermore, surgical techniques vary substantially among surgeons using similar implant designs; thus, the final implant position can result in variable degrees of humeral and glenoid lateralization with all implant designs. Although these effects have reduced the prevalence of dislocation, finite element analysis studies have suggested that glenoid lateralization can increase acromial and scapular spine strain[6-8]. Other studies have suggested that increased humeral lateralization may be protective in the pathogenesis of ASFs, as active strain on the acromion during abduction is theoretically minimized by an increased deltoid moment arm[9,10]. Despite these reports, prior clinical studies have shown conflicting data with regard to the contribution of the final implant position to the prevalence of stress fractures[11-13]. Many of these studies, however, were limited by factors such as low ASF/SSF fracture prevalence and being single implant and surgeon series—resulting in limited generalizability. Thus, the influence of implant position on ASF/SSF fracture prevalence as well as its effect relative to other known risk factors such as osteoporosis and rotator cuff deficiency remain unclear[14]. Better understanding of the clinical implications of implant position in stress fracture prevalence after RSA may help guide counseling, monitoring, and treatment of at-risk patients.

The purpose of this study was to identify patient factors and implant positioning parameters that are associated with the development of ASFs/SSFs after RSA in a large multicenter patient cohort. We hypothesized that final implant position would have a significant effect on the prevalence of ASFs/SSFs following RSA.

Materials and Methods

Study Design

Data on primary and revision RSAs performed between June 2013 and May 2019 across 15 institutions were collected and examined retrospectively. A total of 24 surgeon members of the American Shoulder and Elbow Surgeons (ASES) contributed cases and to the Delphi process. Inclusion and exclusion criteria, study definitions, as well as variables of interest were determined using the Delphi method. Patients who had been followed for a minimum of 3 months after either primary or revision RSA were eligible for inclusion. The primary outcome of interest was the development of an ASF or SSF, defined as pain or loss of motion with associated confirmatory imaging (radiograph or computed tomography [CT] scan) identifying a fracture line, displacement, or evident callus at the acromion or scapular spine[14]. Patients with asymptomatic stress responses or fractures and those diagnosed without confirmatory radiographic evidence were excluded from the fracture group in order to minimize the incorrect inclusion of findings that were not actually ASFs or SSFs, as well as to focus on patients with clinical symptoms. Focusing on symptomatic fractures represents the greatest opportunity to optimize outcomes of RSA.

Delphi Method

The Delphi method is an iterative survey process that is used to reach a consensus across a group of experts[15]. The 24 contributing ASES surgeons utilized the Delphi method to define study parameters and terms, data collection factors, and study design components as previously described[14]. This process was replicated to survey the group and achieve consensus on which factors are the most important in the prevalence of ASFs and SSFs. Consensus was defined as a minimum of 75% agreement on each factor. Anonymity was maintained throughout the iterative process to minimize bias. There were a total of 18 rounds to determine relevant factors and define the study protocol. During each round, closed and open-ended questions were sent to all surgeons and their responses were recorded. Written responses not included in the original question stem for those questions for which 75% consensus was not achieved were added for subsequent rounds. After each round, results were presented to the entire group. There was no attrition between rounds.

The patient and implant factors determined through the Delphi process to be clinically relevant for the regression model assessing the odds of developing an ASF/SSF included age, body mass index (BMI), total glenoid lateral offset (defined as the sum of lateralization contributed by the glenosphere, baseplate, and bone graft if present), neck-shaft angle of the implant design, spacer thickness, liner thickness, duration of follow-up, sex, smoking status, osteoporosis, inflammatory arthritis, revision surgery, a preoperative diagnosis of cuff tear arthropathy or a massive rotator cuff tear, os acromiale, prior ipsilateral shoulder surgery, and utilization of a constrained liner. As determined with the Delphi methodology, the radiographic measurements referencing the final implant position included in our analysis were the lateralization shoulder angle (LSA), distalization shoulder angle (DSA), and lateral humeral offset (LHO). These radiographic measurements provide an integrated assessment of the final implant position, which is the result of both implant selection and surgical technique.

Radiographic Analysis

Two independent reviewers measured the LSA, DSA, and LHO on both preoperative and postoperative radiographs for patients with and without an ASF or SSF. Patients who had a stress fracture and available postoperative radiographs were matched 1:2 to a control cohort (181:358 for LSA and DSA; 157:295 for LHO). The case cohort was not stratified by the location of the stress fractures (i.e., acromion versus scapular spine). All patients included in the radiographic analysis were propensity score-matched by primary diagnosis (cuff tear arthropathy versus other), presence (versus absence) of osteoporosis, and presence (versus absence) of inflammatory arthritis. Measurements were made on a true anteroposterior radiograph of the shoulder, in 30° of rotation with the scapula resting flat against the cassette, as previously described[16]. The LSA was defined as the angle between a line connecting the superior glenoid tubercle to the most lateral border of the acromion and a line connecting the most lateral border of the acromion to the most lateral border of the greater tuberosity[16]. The LSA provides a measurement of the global lateral offset of the joint created by the final implant position. The DSA was defined as the angle subtended by a line connecting the most lateral border of the acromion to the superior glenoid tubercle and a line connecting the superior glenoid tubercle to the most superior border of the greater tuberosity[16]. The DSA provides a measure of global distalization of the humerus relative to the acromion. The LHO is a measure of the distance between parallel lines, 1 drawn down the center of the humeral shaft and the other from the tangential interface point of the glenosphere and humeral implants[17]. The LHO represents an attempt to measure the humeral-sided lateralization created by the implant's final position (Fig. 1). Two separate multivariable analyses were performed, the first utilizing delta LSA and DSA values (change from preoperative to postoperative value), whereas the second utilized only postoperative LSA and DSA values.

Statistical Analysis

Data were analyzed for normality, and appropriate parametric or nonparametric testing was performed. Data were presented as the mean and standard deviation (or median and interquartile range) for continuous variables and as the number and percentage of patients for categorical variables. Patient demographic and implant variables were compared between cohorts

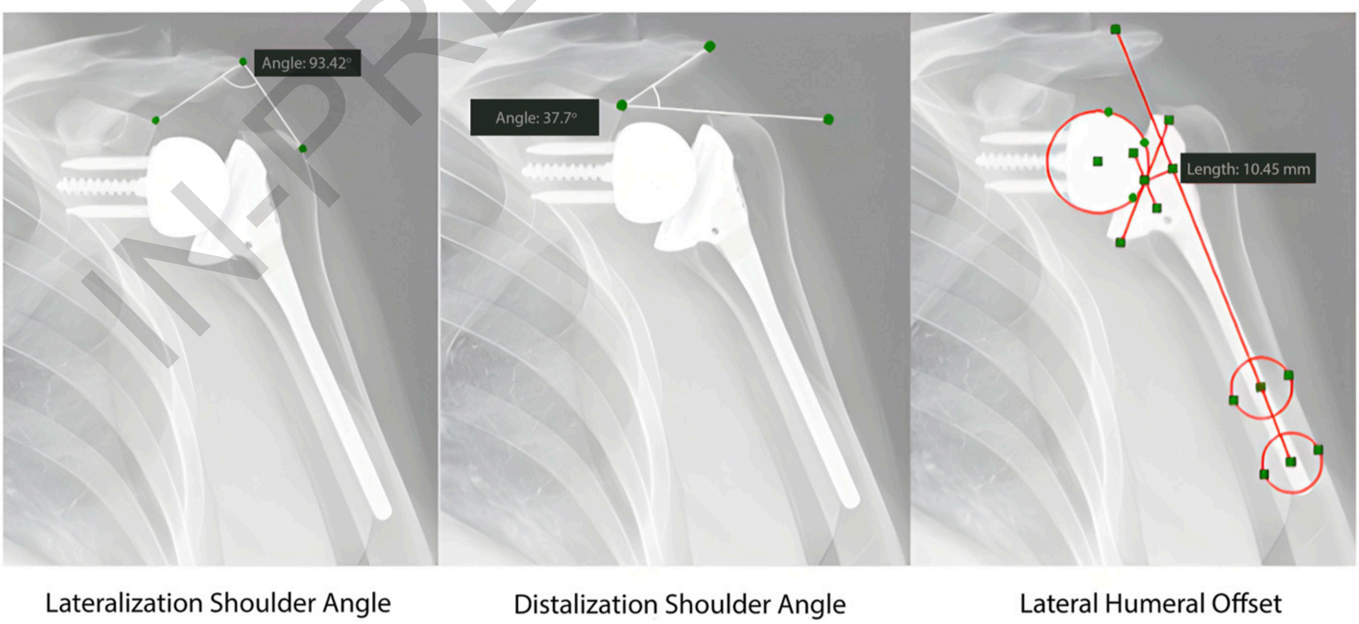

Fig. 1
Radiographic parameters.

with and without an ASF, SSF, or any stress fracture (either an ASF or an SSF) to determine each variable's contribution in predicting these fractures. Categorical variables were analyzed using Pearson chi-square tests, and continuous variables were assessed with Wilcoxon tests. A multivariable logistic regression analysis was performed to determine patient and implant factors predictive of ASFs and SSFs. Results are presented as odds ratios (ORs) with 95% confidence intervals (CIs). Wald statistics were calculated, and analysis of variance (ANOVA) plots were generated to determine the relative strengths of predictor variables. Statistical analysis was performed using open-source R statistical software (R Foundation for Statistical Computing), and multivariable models were fit using the rms package. (Ref- FE HJ. rms: Regression Modeling Strategies. https://cran.r-project.org/web/packages/rms/).

Results

Patient Characteristics (Table I)

Overall, 6,320 patients were included in the study, 239 (3.8%) of whom developed a stress fracture (180 ASFs [2.8%] and 59 SSFs [0.9%]). The mean follow-up was 19.4 ± 15.8 months (range, 3 to 94 months). The mean age was 70.8 ± 8.6 years, and 61% of the patients were female. Half (50%) of the patients had a preoperative diagnosis of rotator cuff disease, which included rotator cuff arthropathy and massive rotator cuff tears. Osteoporosis was present in 13% of the patients, and 11% had inflammatory arthritis. Only 9% of the RSAs were revision procedures.

Implant and Patient Factors

The prevalences of the various factors differed among the 15 institutions. The postoperative fracture rate ranged from 0.7% to 8.1%; osteoporosis rate, from 1.1% to 43.8%; rate of inflammatory arthritis, from 4.1% to 23.3%; and prevalence of patients with a primary diagnosis of rotator cuff disease, from 31.7% to 79.8% ($p < 0.001$ for all) (Table II). On univariate analysis, the total glenoid lateral offset was found to be significantly higher in patients diagnosed with an ASF than in those with no ASF (4.6 ± 3.8 versus 4.0 ± 3.4 mm, p = 0.021). No difference in total glenoid lateral offset was noted between patients with and those without an SSF (3.8 ± 3.7 versus 4.0 ± 3.4, p = 0.39).

After multivariable adjustment, implant and patient factors independently predictive of ASFs were inflammatory arthritis (OR = 2.29, 95% CI = 1.55 to 3.37, $p < 0.001$), a massive rotator cuff tear (OR = 2.05, 95% CI = 1.19 to 3.53, p = 0.010), osteoporosis (OR = 2.00, 95% CI = 1.36 to 2.94, $p < 0.001$), prior shoulder surgery (OR = 1.82, 95% CI = 1.29 to 2.56, $p < 0.001$), cuff tear arthropathy (OR = 1.76, 95% CI = 1.24 to 2.50, p = 0.002), female sex (OR = 1.74, 95% CI = 1.21 to 2.51, p = 0.003), older age (OR = 1.02, 95% CI = 1.00 to 1.05, p = 0.018), and greater total glenoid lateral offset (OR = 1.06, 95% CI = 1.01 to 1.11, p = 0.025). Revision surgery (versus primary surgery) was associated with a lower rate of ASF (OR = 0.38, 95% CI = 0.17 to 0.85, p = 0.019) (Table III).

Factors independently associated with SSFs were female sex (OR = 2.45, 95% CI = 1.25 to 4.81, p = 0.009), rotator cuff

TABLE I Cohort Characteristics Stratified by Stress Fracture Outcome

Parameter	No. of Non-Missing Values	Acromial Fracture (N = 180)	Scapular Spine Fracture (N = 59)	No Fracture (N = 6081)
BMI* *(kg/m^2)*	6304	28.5 ± 6.5	29.0 ± 5.6	30.2 ± 8.1
Age* *(yr)*	6320	72.8 ± 7.6	71.2 ± 7.7	70.8 ± 8.7
Sex *(no. [%])*	6319			
Male		47 (26%)	11 (19%)	2435 (40%)
Female		133 (74%)	48 (81%)	3645 (60%)
Current smoker *(no. [%])*	6074	13 (7%)	5 (9%)	404 (7%)
Follow-up† *(mo)*	6110	17 (10, 31); 22.0 ± 16.5	19 (12, 33); 23.7 ± 16.5	12 (7, 25); 19.3 ± 15.7
Osteoporosis *(no. [%])*	6318	42 (23%)	18 (31%)	758 (12%)
Endocrine disorder *(no. [%])*	6319	31 (17%)	15 (25%)	1309 (22%)
Inflammatory arthritis *(no. [%])*	6320	39 (22%)	14 (24%)	646 (11%)
Prior ipsilateral shoulder surgery *(no. [%])*	5740	70 (39%)	21 (36%)	1831 (33%)
Surgery type *(no. [%])*	6318			
Primary		172 (96%)	57 (97%)	5524 (91%)
Revision		8 (4%)	2 (3%)	555 (9%)
Os acromiale *(no. [%])*	5775	10 (6%)	3 (5%)	195 (4%)

*The values are given as the mean and standard deviation. †The values are given as the median and interquartile range followed by the mean and standard deviation.

TABLE II Institutional Prevalences of Stress Fractures and Previously Identified Risk Factors

		No. (%)			
Institution*	No.	Stress Fracture	Osteoporosis	Inflammatory Arthritis†	Rotator Cuff Disease‡
1	288	2 (0.7%)	50 (17.4%)	22 (7.6%)	151 (52.4%)
2	789	6 (0.8%)	105 (13.3%)	68 (8.6%)	263 (33.3%)
3	441	7 (1.6%)	71 (16.1%)	38 (8.6%)	302 (68.5%)
4	176	3 (1.7%)	19 (10.8%)	41 (23.3%)	95 (54.0%)
5	811	15 (1.8%)	9 (1.1%)	33 (4.1%)	264 (32.6%)
6	676	20 (3.0%)	16 (2.4%)	102 (15.1%)	303 (44.8%)
7	204	7 (3.4%)	16 (7.8%)	22 (10.8%)	134 (65.7%)
8	424	22 (5.2%)	33 (7.8%)	44 (10.4%)	336 (79.2%)
9	515	29 (5.6%)	42 (8.2%)	67 (13.0%)	190 (36.9%)
10	680	41 (6.0%)	109 (16.0%)	95 (14.0%)	324 (47.6%)
11	610	38 (6.2%)	267 (43.8%)	108 (17.7%)	427 (70.0%)
12	319	20 (6.3%)	64 (20.1%)	30 (9.4%)	101 (31.7%)
13	78	5 (6.4%)	1 (1.3%)	7 (9.0%)	41 (52.6%)
14	99	7 (7.1%)	4 (4.0%)	5 (5.1%)	79 (79.8%)
15	210	17 (8.1%)	12 (5.7%)	17 (8.1%)	117 (55.7%)
Total	6320	239 (3.8%)	818 (12.9%)	699 (11.1%)	3127 (49.5%)

*The institutions are listed in order of increasing stress fracture prevalence. †Inflammatory arthritis was defined as the presence of the condition regardless of primary indication for RSA. ‡Rotator cuff disease includes patients with a primary diagnosis of cuff tear arthropathy or a massive rotator cuff tear.

disease (OR = 2.36, 95% CI = 1.35 to 4.14, p = 0.003), osteoporosis (OR = 2.18, 95% CI = 1.22 to 3.89, p = 0.009), and inflammatory arthritis (OR = 2.04, 95% CI = 1.10 to 3.79, p = 0.024) (Table IV).

Radiographic Analysis

Descriptive statistics for the propensity score-matched patients included in the radiographic analysis can be seen in Table V. After multivariable adjustment, a larger ΔLSA was associated with an increased risk of fracture (OR = 1.42, 95% CI = 1.11 to 1.81, p = 0.005), whereas greater LHO was found to be associated with a lower risk of fracture (OR = 0.74, 95% CI = 0.56 to 0.97, p = 0.031) (Fig. 2). Distalization (ΔDSA) was not associated with fracture prevalence (OR = 0.94, 95% CI = 0.71 to 1.23, p = 0.635) (Table VI, Model 1). These associations remained constant when postoperative LSA and DSA values were utilized (Table VI, Model 2) (postoperative LSA: OR = 1.76, 95% CI = 1.21 to 2.56, p = 0.009; postoperative LHO: OR = 0.68, 95% CI = 0.51 to 0.91, p = 0.003; postoperative DSA: OR = 1.01, 95% CI = 0.70 to 1.48, p = 0.942).

Discussion

Our study has shown, through analysis of a large multicenter cohort, that patient factors and final implant position are associated with the development of ASFs and SSFs after RSA. While patient factors, specifically those associated with poor bone density and rotator cuff deficiency, appear to be the stronger predictors of ASFs/SSFs, the final implant position, to a lesser degree, may also play a role in their prevalence. Specifically, our study demonstrated that increased glenoid lateralization and global lateralization were associated with a greater risk of ASFs, while increased humeral-sided lateralization was associated with a lower rate of fracture.

The results of our study largely support the results of prior studies with regard to the effect of patient factors on the prevalence of ASFs/SSFs[14,18]. Our data demonstrate that variables associated with poor bone density (osteoporosis, female sex, older age, and inflammatory arthritis) and rotator cuff deficiency (cuff tear arthropathy and massive rotator cuff tear) are closely linked to the development of ASF/SSF after RSA. While these associations have been reported in previous studies[14,18], the ORs reported in our regression analysis demonstrated that these factors play a larger role in the development of ASF/SSF than many implant-related factors. Considering the consistency and now strength of these associations, efforts to identify, optimize, and counsel patients preoperatively, along with closely monitoring them postoperatively, should be considered.

Prior finite element analyses[6-8] have evaluated the effects of humeral and glenoid component lateralization on acromial and scapular spine strain, and their results corroborate our clinical findings. As glenoid lateralization increases, the center of rotation (CoR) of the shoulder typically also shifts laterally, resulting in a reduction in the deltoid's moment arm and a

TABLE III Multivariable Regression Analysis of Factors Associated with Acromial Stress Fracture

Covariate	OR (95% CI)	P Value*
Age in yr†	1.02 (1.00, 1.05)	**0.018**
BMI in kg/m^2†	0.98 (0.96, 1.00)	0.116
Glenoid lateral offset in mm†‡	1.06 (1.01, 1.11)	**0.025**
Neck-shaft angle in deg†	0.98 (0.96, 1.01)	0.113
Spacer thickness in mm†	1.02 (0.91, 1.14)	0.692
Liner thickness in mm†	1.06 (0.99, 1.12)	0.076
Duration of follow-up in mo†	1.01 (1.00, 1.02)	0.122
Female sex (reference: male)	1.74 (1.21, 2.51)	**0.003**
Current smoker	1.18 (0.64, 2.20)	0.598
Osteoporosis	2.00 (1.36, 2.94)	**<0.001**
Inflammatory arthritis	2.29 (1.55, 3.37)	**<0.001**
Revision surgery (reference: primary procedure)	0.38 (0.17, 0.85)	**0.019**
Primary diagnosis		
Cuff tear arthropathy (reference: other)	1.76 (1.24, 2.50)	**0.002**
Massive rotator cuff tear (reference: other)	2.05 (1.19, 3.53)	**0.010**
Os acromiale	1.49 (0.76, 2.92)	0.248
Prior ipsilateral shoulder surgery	1.82 (1.29, 2.56)	**<0.001**
Non-constrained liner (reference: constrained liner)	0.86 (0.55, 1.34)	0.511

*Boldface denotes significance at an alpha level of 0.05. †For these continuous variables, the odds ratio (OR) represents the risk associated with each 1-unit increase. ‡Total glenoid lateral offset was defined as the sum of the glenosphere, baseplate, and bone graft lateral offsets.

subsequent increase in the deltoid forces required for shoulder abduction[5,9,19]. Finite element analysis studies predicted an increase in acromial and scapular spine strain at low angles of abduction and forward elevation, which increases further with glenoid lateralization[6-8]. Conversely, increased humeral lateralization does not alter the CoR of the shoulder, thus theoretically increasing the deltoid moment arm and decreasing the force necessary to abduct[9,10]. As a result, acromial and scapular spine strains are theoretically decreased with increasing humeral lateralization[20]. Giles et al. previously found that deltoid forces required for abduction are predicated on an interaction between humeral and glenoid component lateralization, indicating that humeral component lateralization can counter the increased deltoid force requirements associated with increased glenoid component lateralization[9]. These notions are supported by our radiographic analysis, which showed a significantly decreased risk of stress fracture with increasing humeral lateralization (LHO). However, caution should still be taken to avoid over-lateralizing the entire joint as we found higher rates of stress fractures with increasing global lateralization (LSA).

TABLE IV Multivariable Regression Analysis of Factors Associated with Scapular Spine Stress Fracture

Covariate	OR (95% CI)	P Value*
Age, per yr†	1.00 (0.97, 1.03)	0.782
Female sex (reference: male)	2.45 (1.25, 4.81)	**0.009**
Glenoid lateral offset, per mm†‡	1.00 (0.93, 1.09)	0.919
Osteoporosis	2.18 (1.22, 3.89)	**0.009**
Inflammatory arthritis	2.04 (1.10, 3.79)	**0.024**
Rotator cuff disease (reference: other)	2.36 (1.35, 4.14)	**0.003**

*Boldface denotes significance at an alpha level of 0.05. †For this continuous variable, the odds ratio (OR) represents the risk associated with each 1-unit increase. ‡Total glenoid lateral offset was defined as the sum of the glenosphere, baseplate, and bone graft lateral offsets.

Prior clinical studies regarding implant positioning parameters contributing to stress fractures after RSA are limited and have reported mixed findings. In contrast with our results, some authors have found greater global lateralization, as measured radiographically, to be protective[21-23]. Others have identified increased global lateralization as a risk for stress fracture[24]. These studies' discrepant results may be explained by their small number of included stress fractures, confounding patient and implant factors, varying methods of radiographic measurements, and failure to evaluate glenoid and humeral-sided lateralization independently. Prior clinical studies have similarly reported mixed results relating to the effect of implant design on the risk of ASF[18,25-28]. These

TABLE V Comparison of the Characteristics of the Propensity Score-Matched Cohorts Used in the Radiographic Analysis*

	Lateralization Shoulder Angle (LHA) and Distalization Shoulder Angle (DSA) Analysis			Lateral Humeral Offset (LHO) Analysis		
Parameter	No. of Non-Missing Values	Fracture (N = 181)	No Fracture (N = 358)	No. of Non-Missing Values	Fracture (N = 157)	No Fracture (N = 295)
BMI* *(kg/m²)*	539	28.6 ± 6.5	29.4 ± 6.5	452	28.5 ± 6.3	29.3 ± 6.6
Age* *(yr)*	539	71.8 ± 7.6	71.8 ± 8.5	452	72.0 ± 7.6	71.6 ± 8.4
Sex *(no. [%])*	539			452		
Male		39 (21.5%)	119 (33.2%)		35 (22.3%)	97 (32.9%)
Female		142 (78.5%)	239 (66.8%)		122 (77.7%)	198 (67.1%)
Current smoker *(no. [%])*	539	12 (6.6%)	18 (5.0%)	452	7 (4.5%)	18 (6.1%)
Follow-up† *(mo)*	539	15 (10, 31); 21.7 ± 16.1	12 (6, 24); 17.6 ± 15.6	452	15 (10, 29); 1.3 ± 16.2	12 (6, 24); 17.2 ± 15.5
Prior ipsilateral shoulder surgery *(no. [%])*	470	73 (40.3%)	90 (31.1%)	418	65 (41.4%)	88 (29.8%)
Surgery type *(no. [%])*	539			452		
Primary		180 (99.4%)	352 (98.3%)		156 (99.4%)	289 (98.0%)
Revision		1 (0.6%)	6 (1.7%)		1 (0.6%)	6 (2.0%)
Os acromiale *(no. [%])*	470	13 (7.2%)	8 (2.2%)	452	10 (6.4%)	7 (2.4%)
Covariates used in propensity score matching‡ *(no. [%])*						
Osteoporosis	539	49 (27.2%)	90 (25.1%)	451	34 (21.7%)	57 (19.3%)
Primary diagnosis of cuff tear arthropathy	539	107 (59.1%)	217 (60.6%)	452	89 (56.7%)	172 (58.3%)
Inflammatory arthritis	539	42 (23.2%)	75 (20.9%)	451	35 (22.3%)	62 (21.0%)

*The values are given as the mean and standard deviation. †The values are given as median and interquartile range followed by the mean and standard deviation. ‡These variables were the 3 covariates used in propensity score-matching of the "fracture" and "no fracture" cohorts.

inconsistencies may be due to a large variability in the amount of lateralization among similarly categorized implants[29] as well as variation in surgical technique that may impact the true amount of lateralization achieved. As such, all implants traditionally considered to have a similar design (e.g., a lateralized humeral design) may not act similarly in terms of their effect on stress fracture prevalence. Our study of patients with ASF or SSF attempted to integrate both surgical technique and implant design factors through radiographic analysis of the ultimate implant position regardless of implant design. Given the diversity of implant designs and variability in surgical technique, future studies should consider including a radiographic analysis of final implant position as opposed to characterizing implants in a binary fashion regarding their location of lateralization.

When determining the clinical applicability of our data, surgeons should recognize that the strength of the association between implant factors and ASF/SSF is much less than that between patient-specific factors and ASF/SSF. Therefore, appropriately identifying, optimizing, and counseling higher-risk patients (e.g., those with osteoporosis or rotator cuff deficiency) should be prioritized throughout the perioperative period. Also, our implant-related findings should be considered in the setting of the known advantages of glenoid-sided lateralization, including improved external rotation and lower rates of scapular notching and impingement[30]. In fact, the influence of final implant positioning on stress fracture prevalence may become even less relevant given the growing utilization of RSA in patients with osteoarthritis (versus cuff tear arthropathy), who are at a lower risk

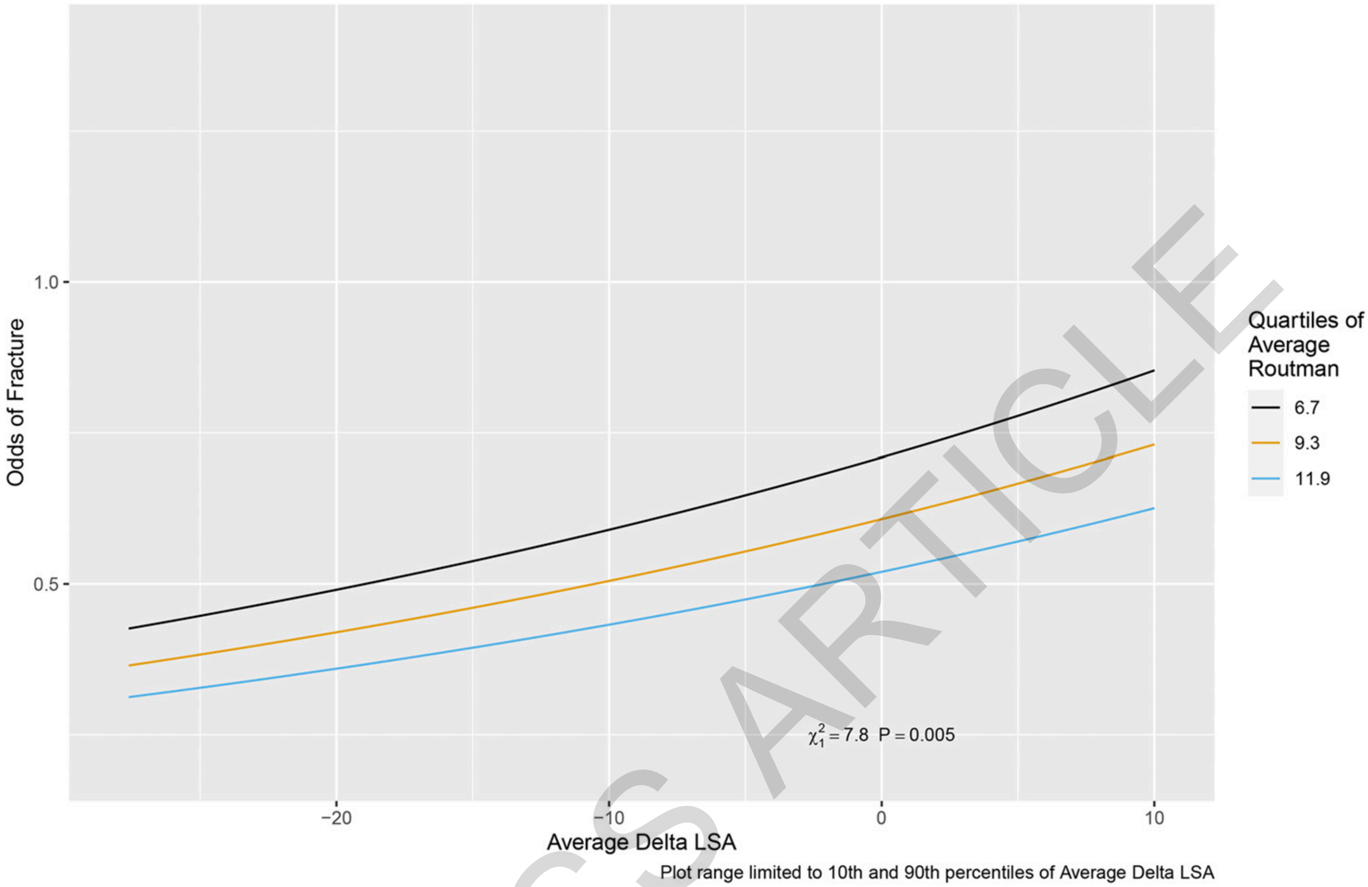

Fig. 2
Effects of the delta lateralization shoulder angle (ΔLSA) and lateral humeral offset (measured as described by Routman et al.[17]) on stress fracture risk.

TABLE VI Multivariable Regression Analysis of Radiographic Factors Associated with Stress Fracture

Covariate	OR (95% CI)*	P Value†
Model 1‡		
Average ΔDSA *(deg)*	0.94 (0.71, 1.23)	0.635
Average ΔLSA *(deg)*	1.42 (1.11, 1.81)	**0.005**
Average LHO§ *(mm)*	0.74 (0.56, 0.97)	**0.031**
Model 2#		
Average postoperative DSA *(deg)*	1.01 (0.70, 1.48)	0.942
Average postoperative LSA *(deg)*	1.76 (1.21, 2.56)	**0.009**
Average LHO§ *(mm)*	0.68 (0.51, 0.91)	**0.003**

*The odds ratio (OR) represents the risk associated with each 1-unit increase. †Boldface denotes significance at an alpha level of 0.05. ‡Model 1 utilized the change in the distalization shoulder angle (ΔDSA) and in the lateralization shoulder angle (ΔLSA) from preoperative to postoperative values. §Lateral humeral offset (LHO) is a measure of humeral lateralization. #Model 2 utilized postoperative DSA and LSA values.

for ASFs, as well as emerging data suggesting that nonoperative management of ASFs lateral to the glenoid face may result in outcomes similar to those in patients who do not sustain an ASF[3,31].

The strengths of our study include the multicenter patient cohort and Delphi design. Our data were derived from the cases performed by 24 surgeons utilizing multiple RSA implant types, which allowed for an analysis of a large number of ASFs and SSFs. This study also had several limitations that should be noted. The first is the substantial variation in the fracture rate among institutions in our series (range, 0.7% to 8.1%). As we were unable to adjust for surgical technique in our regression analysis due to a limitation in the available degrees of freedom, we acknowledge an inevitable variability among the surgeons (with regard to patient populations, surgical technique, imaging modality to diagnose ASF/SSF, etc.) that may have led to differing complication rates. With a large variability in institutional rates of ASF/SSF, it remains possible that some institutions over- or under-reported the number of fractures. The radiographic analysis helped to control for surgical technique factors, as the LSA, DSA, and LHO were based on the final implant position, thus incorporating the effects of both surgical technique and implant selection. The decision to focus on the radiographically determined position (i.e., "final implant position"), as opposed to characterizing the implants by their design (e.g., "lateralized" or "medialized"), was made to minimize confounding due to variability in implant placement. Specifically, the most accurate technique to identify the effect of a certain implant is to assess its ultimate position radiographically, as both implant design and surgical technique contribute to the final implant position.

The second limitation of this study is the fact that humeral-sided implants were evaluated only in our regression analysis of the radiographic data (Table VI), which did not control for variations in implant design selection. It was decided, through the Delphi method, to exclude humeral-sided implant factors from our primary regression analysis (Tables III and IV) in order to minimize the potential for confounding due to varying surgical technique. Furthermore, an independent measurement of glenoid-sided lateralization was not included in our radiographic evaluation. Therefore, it is unclear if the significantly higher rate of stress fractures associated with a larger LSA (both the change and the postoperative value was in fact due to excessive global lateralization—given the protective association of humeral lateralization in this regression analysis—or if it represented the residual risk of glenoid lateralization.

The third limitation of this study is its retrospective design, which made it impossible to prove causation. Instead, we could only show an association between certain implant factors and ASFs/SSFs. Fourth, the results of our Delphi questioning, including surgeon opinions, relied on a consensus threshold, and thus a small subset of shoulder surgeons may have remained in disagreement with established definitions. However, we think that the 24 shoulder surgeons included are a representative cohort in terms of practice patterns around the U.S. Fifth, other previously identified risk factors for stress fractures, including screw position and damage to the coracoacromial ligament, were not analyzed[32-35]. Despite the prior studies demonstrating screw position as a possible risk factor for SSFs, the decision was made during the Delphi process to not specifically study that factor due to the difficulty in accurately characterizing screw placement on radiographs alone, as many patients did not have postoperative CT scans. However, future studies assessing screw placement as a risk factor for SSFs among patients with postoperative CT scans should be considered.

Lastly, it is possible that some patients may have developed an ASF or SSF at a later date, given our 3-month minimum follow-up period. While this may have led to certain patients being miscategorized in our analysis, it is likely that few were, given our 19-month mean follow-up. Furthermore, a minimum follow-up of 3 months was determined by the Delphi process to maximize the number of patients (and stress fractures) included in our cohort, allowing for additional degrees of freedom in our regression analysis.

Conclusion

Patient factors associated with poor bone density and rotator cuff deficiency appear to be the strongest predictors of ASF/SSF after RSA. To a lesser degree, implant and surgical technique factors are associated with ASF/SSF, with increased humeral lateralization being associated with lower fracture rates and glenoid-sided and global lateralization associated with higher fracture rates. ■

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