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The association between humeral lengthening and clinical outcomes after reverse shoulder arthroplasty: a systematic review and meta-analysis

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Background: The purpose of this study was to evaluate the relationship between humeral lengthening and clinical outcomes after reverse shoulder arthroplasty (RSA) with stratification based on measurement method and implant design.
Methods: This systematic review was performed using PRISMA-P guidelines. PubMed/Medline, Cochrane Trials, and Embase were queried for articles evaluating the relationship between humeral lengthening and clinical outcomes inclusive of range of motion (ROM), strength, outcome scores, and pertinent complications (acromial and scapular spine fractures, nerve injury) after RSA. The relationship between humeral lengthening and clinical outcomes was reported descriptively overall and stratified by measurement method and implant design (globally medialized vs. lateralized). A positive association was defined as increased humeral lengthening being associated with greater ROM, outcome scores, or a greater incidence of complications, whereas a negative association denoted that increased humeral lengthening was associated with poorer ROM, outcome scores, or a lower incidence of complications. Meta-analysis was performed to compare humeral lengthening between patients with and without fractures of the acromion or scapular spine.
Results: Twenty-two studies were included. Humeral lengthening was assessed as the acromiohumeral distance (AHD), the distance from the acromion to the greater tuberosity (AGT), the acromion to the deltoid tuberosity (ADT), and the acromion to the distal humerus (ADH). Of 11 studies that assessed forward elevation, a positive association with humeral lengthening was found in 6, a negative association was found in 1, and 4 studies reported no association. Of studies assessing internal rotation (n = 9), external rotation (n = 7), and abduction (n = 4), all either identified a positive or lack of association with humeral lengthening. Studies assessing outcome scores (n = 11) found either a positive (n = 5) or no (n = 6) association with humeral lengthening. Of the studies that assessed fractures of the acromion and/or scapular spine (n = 6), 2 identified a positive association with humeral lengthening, 1 identified a negative association, and 3 identified no association. The single study that assessed the incidence of nerve injury identified a

Institutional review board approval was not required for this review article.

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positive association with humeral lengthening. Meta-analysis was possible for AGT (n = 2) and AHD (n = 2); greater humeral lengthening was found in patients with fractures for studies using the AGT (mean difference 4.5 mm, 95% CI 0.7-8.3) but not the AHD. Limited study inclusion and heterogeneity prohibited identification of trends based on method of measuring humeral lengthening and implant design.

Conclusion: The relationship between humeral lengthening and clinical outcomes after RSA remains unclear and requires future investigation using a standardized assessment method.

Level of evidence: Level IV; Systematic Review

Keywords: Arm; humerus; distalization; inverted shoulder; upper extremity; acromial fracture; scapular spine fracture

Reverse shoulder arthroplasty (RSA) was first introduced for the surgical management of rotator cuff arthropathy.[4] Since its introduction, indications have expanded to include rotator cuff intact glenohumeral arthritis, irreparable rotator cuff tears, failed shoulder arthroplasty, and proximal humerus fractures.[8,12,21,24,31] In line with the theory that optimal deltoid function is achieved through optimizing fiber recruitment and the length of contractile elements according to Blix,[45] prior work has demonstrated that adequate tensioning of the deltoid muscle achieved both through distalization and lateralization is crucial to restoring function and preventing prosthesis dislocation.[22,32] Patients receiving early Grammont-style prostheses with a more medial center of rotation (COR) often lacked rotational motion postoperatively and developed radiographic scapular notching.[6,25] However, contemporary lateralized RSA designs have consistently demonstrated improvement in rotational motion with lower rates of scapular notching.[1,13,15,19,25,30,44,54,66]

Many surgeons believe that excessive distalization of the humerus in RSA predisposes patients to acromion and scapular spine fractures and to neurological injury.[3,9,10,32,33,52] However, the results of clinical studies remain discordant. Reports range from greater humeral lengthening being associated with more favorable (ie, positive relationship) range of motion (ROM),[22,34,47] to having no relationship,[11,14,23,55] or to having a poorer ROM (ie, negative relationship). Similarly, although some studies have identified a positive association between humeral lengthening and the incidence of fracture and nerve injury,[18,27,33,51,58,60] others report no association.[9,35,39,47,60,61] One possible explanation for this variability is the large variation in prosthesis design and humeral component placement between studies. Particularly, humeral lateralization has been shown to increase strain on the acromion and scapular spine in biomechanical studies.[38,63,64] Reconciling these findings and identifying the degree to which humeral lengthening affects complication rates and patient outcomes will allow surgeons to tailor implant selection and placement to individual patient needs.

The goal of this review was to determine the association between humeral lengthening and clinical outcomes of RSA. We hypothesized that increased humeral lengthening would be associated with greater range of motion in elevation and an increased incidence of postoperative complications with prosthetic design differences.

Methods

Article identification and selection

This study followed criteria set forth by the Preferred Reporting Items for Systematic reviews and Meta-Analysis Protocols (PRISMA-P) statement.[42] PubMed, Cochrane Trials, and Embase databases were queried on April 3, 2022, for literature evaluating the relationship between humeral lengthening and clinical outcomes for patients following reverse shoulder arthroplasty published since inception. The following search strategy was utilized: (“arm” OR “humeral” OR “humerus” OR “subacromial” OR “acromiohumeral” OR “tuberosity” OR “tubercle” OR “deltoid”) AND (“length” OR “lengthening” OR “distance” OR “displacement” OR “distalization”) AND (“reverse” OR “inverted”) AND (“shoulder”) AND (“arthroplasty” OR “replacement”). Studies were excluded based on the following criteria: non-English text, only abstract available, review or meta-analysis, case report or fewer than 10 patients, biomechanical or cadaveric study, no assessment of humeral lengthening, or no assessment of the relationship between humeral lengthening and a clinical outcome (Fig. 1). Three investigators (B.D.H., R.J.C., B.M.A.) screened articles by title, abstract, and full-text, when appropriate. The senior author was consulted to resolve discrepancies or when applicability of criteria was uncertain; a consensus decision was made for all such cases.

Outcome measures and data extraction

The primary outcome was whether included studies identified an association between humeral lengthening and any clinical outcomes. Clinical outcomes eligible for inclusion were ROM, shoulder strength, patient-reported or combined patient- and physician-reported outcome scores, and the incidence of complications. All ROM, strength, and outcome scores were collected

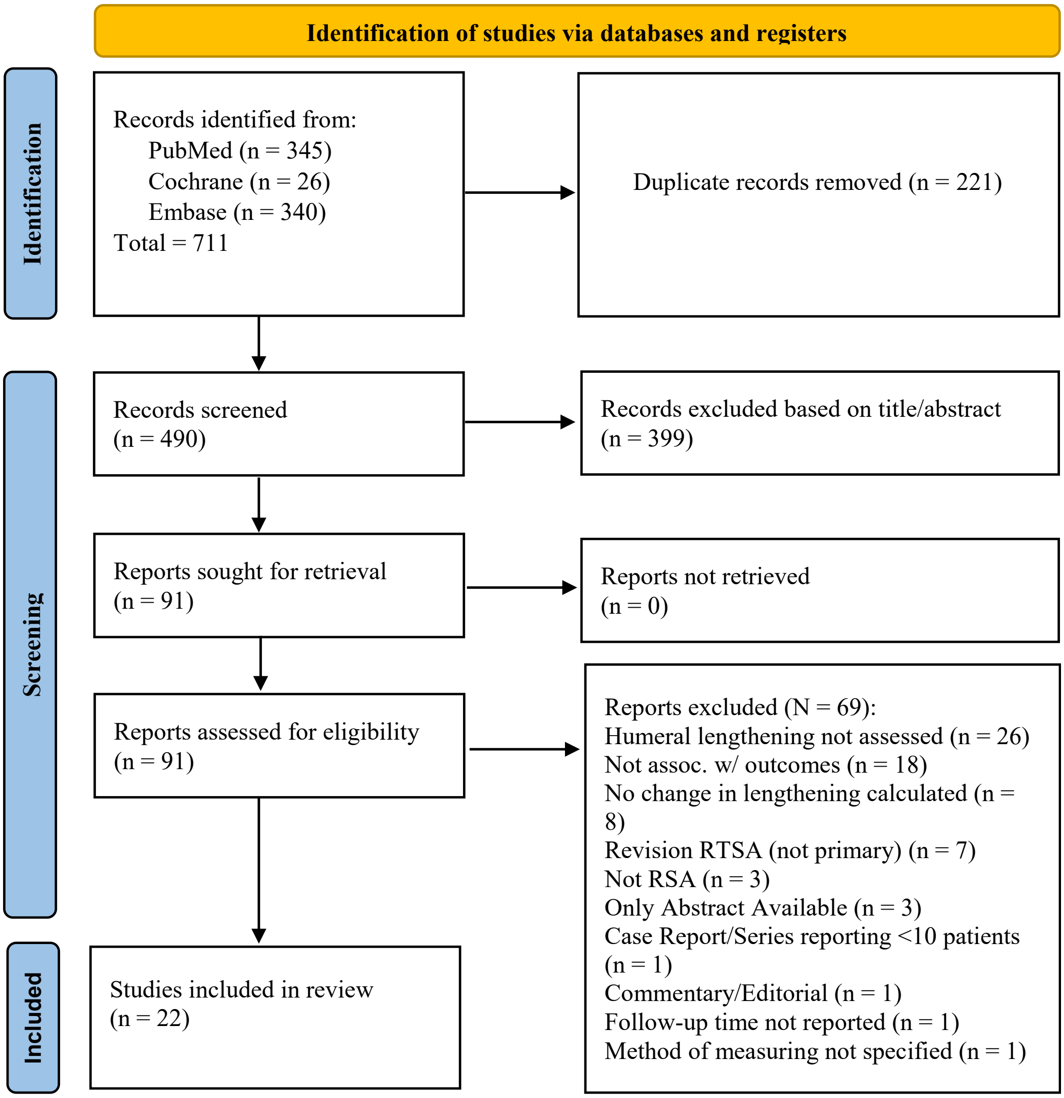

Figure 1 PRISMA flowchart of the study selection criteria.

from included studies where available. Complications assessed were limited to those previously hypothesized to be related to excess humeral lengthening; these included fractures of the acromion or scapular spine and nerve injuries.[4,6,9,22] Three investigators (B.D.H., R.J.C., B.M.A) used a data extraction spreadsheet for the documentation of all relevant data including patient age, number of male and female patients, mean and minimum time of follow-up, as well as the aforementioned clinical outcomes.

Risk of bias assessment

Using the Methodological Index for Non-Randomized Studies (MINORS) criteria, a single investigator (B.D.H) independently assessed risk of bias (Table I).[57] Briefly, the numerical scale is composed of 12 questions, with an ideal score of 16 points for non-randomized studies and an ideal score of 24 points for comparative studies. Items are scored as 0 for not reported, 1 for reported but inadequate, and 2 for reported and adequate.

Statistical analysis

Demographic data of patients from included articles were summarized by calculating weighted means based on the number of patients in each study. Similarly, the weighted mean humeral lengthening was calculated separately based on anatomic landmarks utilized and further stratified by implant design as previously classified by Werthel et al.[63] Stratifications based on implant design included inlay vs. onlay and global lateralization (medialized or minimally lateralized vs. lateralized, or highly lateralized). Whether an association was identified between humeral lengthening and clinical outcomes (ROM, outcome scores,

Table I Demographics of included studies with the risk of bias assessed using the Methodological Index for Non-Randomized Studies (MINORS) criteria

Author	Study design	Total score	No. of RTSAs	Follow-up		Mean age, yr	% Female
				Mean	Minimum		
Greiner et al (2010)[14]	Retrospective	13	23	26	12	73.1	61
Jobin et al (2012)[22]	Prospective	13	37	16	6	76	73
Dubrow et al (2014)[9]	Retrospective	12	125	19.7	1	71.7	72
Kadum et al (2014)[23]	Prospective	12	27	39	15	72	85
Sabesan et al (2016)[51]	Retrospective	12	76	37	13	72.2	64
Werner et al (2016)[61]	Retrospective	12	44	11.1	6	75	77
Werner et al (2017)[60]	Retrospective	13	56	30.1	24	74.6	73
Yoon et al (2017)[65]	Prospective	13	35	16.5	12	74.8	77
Werthel et al (2018)[62]	Retrospective	20*	60	27	24	71.5	73
Roberson et al (2019)[48]	Retrospective	12	108	68	NA	69	65
Fischer et al (2020)[11]	Prospective	13	35	6.3	5.8	74.4	63
Haidamous et al (2020)[15]	Retrospective	13	426	12.9	3	72.5	58
Kim et al (2020)[27]	Retrospective	12	182	58.5	24	72.8	65
Lee et al (2020)[36]	Retrospective	20*	102	31.9	NA	74.5	85
Romano et al (2020)[49]	Retrospective	12	35	55.2	24	71	71
Schenk et al (2020)[53]	Retrospective	13	105	50	4	73.8	81
Zmistowski et al (2020)[67]	Retrospective	13	401	13	3	72.4	63
Berthold et al (2021)[2]	Retrospective	13	61	37.2	24	69.2	56
Haidamous et al (2021)[17]	Retrospective	13	133	12.3	12	74	54
Hochreiter et al (2021)[20]	Retrospective	19*	115	51	24	72.4	56
Haidamous et al (2022)[16]	Retrospective	21*	78	NA	12	69.4	49
Kim et al (2022)[28]	Retrospective	12	123	30.59	12	73.1	85

RTSAs, reverse total shoulder arthroplasties; *NA*, not available.
Noncomparative studies have a maximal MINORS score of 16.
* A comparative study that has a maximal score of 24.

and complications) by included studies was summarized for all studies and stratified by the method used to assess humeral lengthening and implant design.

Meta-analysis was performed to compare the mean change in humeral lengthening between patients with vs. without complications. We anticipated that the design of the included studies and methodology involved in data collection would result in substantial heterogeneity; thus, we elected to use a random effects model a priori.[5] The I^2 statistic was used to assess the heterogeneity of results. The true effect size in 95% of the population (95% prediction interval [PI]) was calculated using the variance of true effects (T^2) and thus the standard deviation of true effects (T). Meta-analysis was performed using the metafor package.[59] All statistical analyses were performed using R software (version 4.2.0; R Core Team, Vienna, Austria) with an α of 0.05.

Results

Study characteristics

Of the 711 studies initially queried, 490 unique articles were identified and 91 underwent full-text screening (Fig. 1). In total, 22 articles were included: a summary of included articles is presented in Tables I and II. Included articles reported on a total of 2393 shoulders (66% female) with a weighted mean age of 73 years (range: 69-76 years) and follow-up of 28 months (range: 6.3-68 months) (Table III).

Radiographic assessment of humeral lengthening

Humeral lengthening was most commonly assessed by measuring the acromiohumeral distance (AHD) (1095 shoulders in 5 studies), followed by the distance from the acromion to the greater tuberosity (AGT) (1020 shoulders in 11 studies), the acromion to the deltoid tuberosity (ADT) (727 shoulders in 7 studies), and the acromion to the distal humerus (ADH) (106 shoulders in 3 studies) (Table IV). Examples of each of these methods are shown in Fig. 2. Four articles included 2 methods of assessing humeral lengthening that used different anatomic landmarks. The mean humeral lengthening decreased when the anatomic landmark on the humerus was more distal (Table IV). The weighted mean humeral lengthening based on the anatomic landmark used for radiographic measurements did not demonstrate a trend based on inlay vs. onlay (Table V) or global lateralization (Table VI).

Table II Prosthesis design and humeral lengthening assessment method with summary of the influence of humeral lengthening on clinical outcomes

Author	Year	Humeral lengthening		Prosthesis design			Was humeral lengthening associated with a clinical outcome?			
		Method	Mean ± SD	Name	Inlay/onlay	Global lateralization*	ROM	Outcome score(s)	Acromial or SS fracture	Nerve injury
Greiner et al[14]	2010	ADH	17.0 ± 13.0	DePuy Delta III	Inlay	M	None	None (Constant, DASH)	NA	NA
Jobin et al[22]	2012	ADT AGT	21.0 ± 10.0 23.0 ± 9.0	Multiple[†]	Inlay	ML	Positive (aFE)	None (ASES, SST)	NA	NA
Dubrow et al[9]	2014	AGT	27.5	Tornier Aequalis	Inlay	M	NA	NA	None	NA
Kadum et al (2014)[23]	2014	ADH	16.0 ± 8.0	Biomet TESS	Inlay	L	None	None (QuickDASH) Positive (EQ-5D)	NA	NA
Sabesan et al[51]	2016	AGT ADT	25.6 ± 16.5 20.4 ± 18.2	DePuy Delta III; Tornier Aequalis	Inlay	M	Negative (aFE)	None (Constant, ASES)	NA	NA
Werner et al[61]	2016	AGT	25.0	Aequalis Ascend Flex	Onlay	L	NA	NA	None	NA
Werner et al[60]	2017	ADH	22.0 ± 16.9	Aequalis Ascend Flex	Onlay	L	Positive (IR), mixed (aFE), negative (aER)	Positive (Constant)	None	None
Yoon et al[65]	2017	ADT	27.0 ± 12.1	Aequalis Ascend Flex	Inlay	M	NA	Positive (Constant)	NA	NA
Werthel et al[62]	2018	AGT	19.1 ± 7.2	Multiple[‡]	NA	NA	NA	NA	Positive	NA
Roberson et al[48]	2019	AGT	20.6	Unspecified	NA	NA	Positive (aFE, aER)	Positive (ASES)	NA	NA
Fischer et al[11]	2020	ADT	22.7 ± 10.1	Unspecified	NA	NA	None (aFE)	NA	NA	NA
Haidamous et al[15]	2020	AHD	33.9 ± 9.1	Multiple[§]	NA	NA	None (aFE, aER)	NA	NA	NA
Kim et al[27]	2020	AGT	21.2 ± 8.6	Multiple[‖]	NA	NA	NA	None (Constant)	NA	Positive
Lee et al[36]	2020	ADT	20.3 ± 13.3	Exactech Equinoxe	Onlay	L	Positive (aFE, aER, aIR, abduction)	Positive (Constant, ASES)	NA	NA
Romano et al[49]	2020	AGT ADT	28.6 ± 3.0 26.9 ± 4.1	Exactech Equinoxe	Onlay	L	None (aFE, aER, aIR, abduction)	None (Constant)	NA	NA
Schenk et al[53]	2020	AGT	21.9 ± 8.0	Zimmer Inverse/ Reverse	Onlay	HL	NA	NA	None	NA
Zmistowski et al[67]	2020	AHD ADT	27.3 ± 9.1 20.2 ± 19.5	Unspecified	NA	NA	NA	NA	Negative	NA
Berthold et al[2]	2021	AHD	21.2 ± 1.3	Arthrex Univers Revers 135°	Semi-inlay	ML	Positive (aFE), None (aER, aIR, abduction)	None (Constant)	NA	NA
Haidamous et al[17]	2021	AGT	31.0 ± 8.4	Arthrex Univers Revers	Semi-inlay	ML	None (aIR)	NA	NA	NA

(*continued on next page*)

Table II Prosthesis design and humeral lengthening assessment method with summary of the influence of humeral lengthening on clinical outcomes (*continued*)

Author	Year	Humeral lengthening		Prosthesis design			Was humeral lengthening associated with a clinical outcome?			
		Method	Mean ± SD	Name	Inlay/onlay	Global lateralization*	ROM	Outcome score(s)	Acromial or SS fracture	Nerve injury
Hochreiter et al[20]	2021	AGT	20.9 ± 6.6	Zimmer Inverse/Reverse	Onlay	HL	Positive (aIR)	NA	NA	NA
Haidamous et al[16]	2022	AHD	24.3 ± 8.0	Arthrex Univers Revers 135°	Semi-inlay	ML	None (aFE, aER)	NA	NA	NA
Kim et al[28]	2022	AHD	19.0 ± 0.8	Unspecified	NA	NA	None (aIR)	NA	NA	NA

ADH, acromion to distal humerus; *ADT*, acromion to deltoid tuberosity; *AGT*, acromion to greater tuberosity; *AHD*, acromiohumeral distance; *SD*, standard deviation; *M*, medialized; *ML*, minimally lateralized; *L*, lateralized; *NA*, not applicable; *HL*, highly lateralized; *ROM*, range of motion; *aFE*, active forward extension; *IR*, active internal rotation; *aER*, active external rotation; *aIR*, XXXX; *DASH*, Disabilities of the Arm, Shoulder, and Hand questionnaire; *ASES*, American Shoulder and Elbow Surgeons Standardized Shoulder Assessment Form; *SST*, Simple Shoulder Test; *SS*, subscapular.

* Implant classification adopted from Werthel et al.[62]

† Zimmer Trabecular Metal; DePuy Delta III; Tornier Aequalis.

‡ DePuy DeltaXtend; Zimmer Inverse/Reverse; Tornier Aequalis; DePuy Delta III; Encore RSP.

§ Arthrex Univers Revers; Altivate Reverse; Aequalis Ascend Flex.

‖ Tornier Aequalis II; Biomet Comprehensive; Exactech Equinoxe; Tornier Ascend Flex.

Range of motion

Fourteen studies (64%) assessed the relationship between humeral lengthening and active ROM, of which eight (57%) identified an association (Table VII). Of the 11 studies that assessed forward elevation, 6 (55%) identified a positive association with humeral lengthening, 1 (9%) identified a negative association, and 4 (36%) identified no association. Stratification by implant design found that of the inlay, onlay, and semi-inlay designs, only 1 study (Sabesan et al[51]) using an inlay implant with a lateralization class of medialized/minimally lateralized found a negative relationship between lengthening and forward elevation (FE). The single study by Sabesan et al[51] that identified a negative association reported a negative correlation between postoperative FE and ΔAGT ($R = -0.27$, $P = .045$) and between improvement in FE and ΔADT ($R = -0.47$, $P = .031$) using an inlay humerus and globally medialized design; the authors suggested this finding may be explained by acromion fractures, axillary nerve injury, and abduction contracture in patients with overlengthening of the humerus. Of the studies that assessed internal rotation (IR) (n = 9), external rotation (ER) (n = 7), and abduction (n = 4), all either identified a positive association with humeral lengthening or found no association.

Strength

None of the included studies assessed the relationship between humeral lengthening and shoulder strength.

Outcome scores

Eleven studies (50%) sought to determine the relationship between humeral lengthening and outcome scores, of which 6 (55%) identified an association (Table VIII). Outcome scores assessed in descending order of frequency were the Constant score (n = 8), the American Shoulder and Elbow Surgeons Standardized Shoulder Assessment Form (ASES) (n = 4), the Simple Shoulder Test (SST) (n = 1), the Disabilities of the Arm, Shoulder, and Hand questionnaire (DASH) (n = 1), the quick DASH (QuickDASH) (n = 1), and the EuroQol-5D score (EQ-5D) (n = 1). Three of 8 studies assessing the Constant score (38%), 2 of the 4 studies assessing the ASES score (50%), and the single study assessing the EQ-5D score identified a positive association between humeral lengthening and outcome scores; the remaining studies found no association. Stratification by inlay vs. onlay design type and by global lateralization did not reveal a trend.

Complications

Nine studies (9 of 22, 41%) assessed the relationship between humeral lengthening and either fracture of the

Table III Study demographics and follow-up

Demographic	Weighted value	Studies reporting, % (n)
Mean shoulders per study, n (median; IQR)	109 (77; 23-426)	100 (22)
Mean age, yr (range)	72.5 (69-76)	100 (22)
Mean follow-up length, months (range)	28.0 (6.3-68)	95 (21)
Mean minimum follow-up, months (range)	10.1 (1-24)	91 (20)
Mean proportion of female patients, % (range)	65.7 (48.7-85.3)	100 (22)

IQR, interquartile range.

Table IV Humeral lengthening characteristics from included studies (n = 22)

Measure	Weighted mean (range)	Studies reporting, % (n)	Shoulders reporting, % (n)
AHD	28.4 (19.0-33.9)	22.7 (5)	45.8 (1095)
AGT	23.9 (19.1-31.0)	50.0 (11)	42.6 (1020)
ADT	21.0 (20.2-27.0)	31.8 (7)	30.4 (727)
ADH	19.4 (16.0-22.0)	13.6 (3)	4.4 (106)

AHD, acromiohumeral distance; *AGT*, acromion to greater tuberosity; *ADT*, acromion to deltoid tuberosity; *ADH*, acromion to distal humerus.

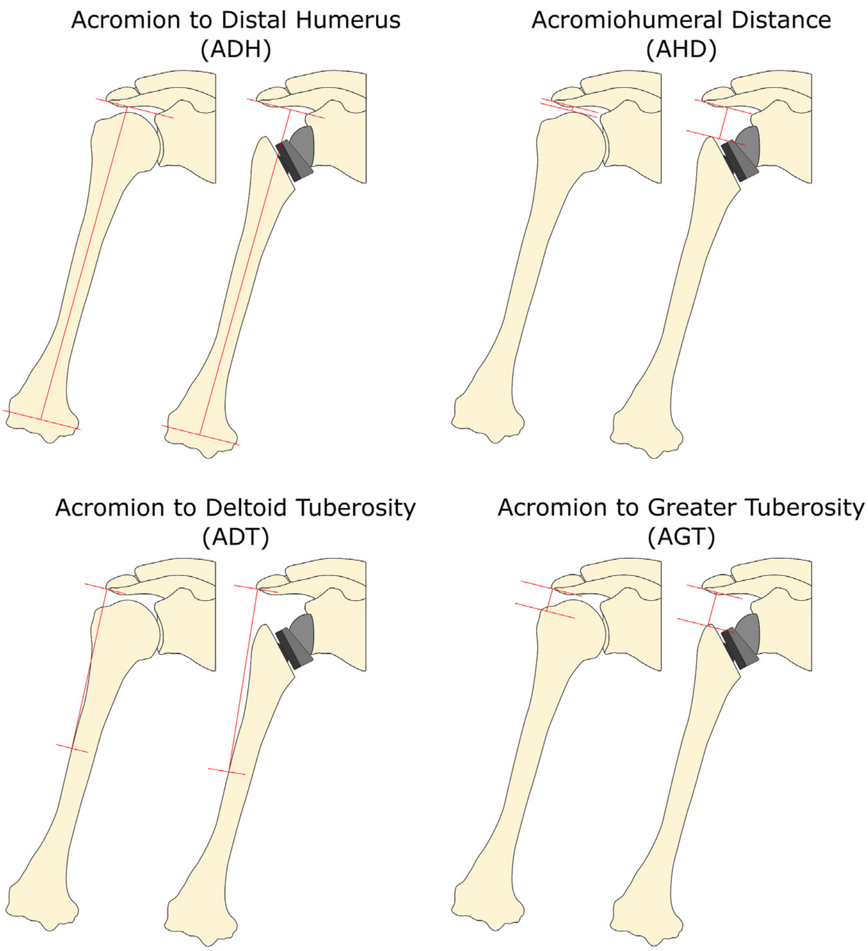

Figure 2 Methods of assessing humeral lengthening on radiographs included the distance from the acromion to the distal humerus (ADH), the acromiohumeral distance/interval (AHD), distance from the acromion to the deltoid tuberosity (ADT), and distance from the acromion to the greater tuberosity (AGT).

Table V Humeral lengthening characteristics stratified by inlay vs. onlay design from included studies with classified implants (n = 16)

Measure	Classification*	Weighted mean (range)	Studies reporting, % (n)	Shoulders reporting, % (n)
AHD	Semi-inlay	23.0 (21.2-24.3)	13.3 (2)	13.2 (139)
AGT	Semi-inlay	31.0 (31.0-31.0)	6.7 (1)	12.6 (133)
	Onlay	22.8 (20.9-28.6)	26.7 (4)	28.4 (299)
	Inlay	26.2 (23.0-27.5)	20.0 (3)	22.6 (238)
ADT	Onlay	22.0 (20.3-26.9)	13.3 (2)	13.0 (137)
	Inlay	22.1 (20.4-27.0)	20.0 (3)	14.1 (148)
ADH	Onlay	22.0 (22.0-22.0)	6.7 (1)	5.3 (56)
	Inlay	16.5 (16.0-17.0)	13.3 (2)	4.8 (50)

AHD, acromiohumeral distance; *AGT*, acromion to greater tuberosity; *ADT*, acromion to deltoid tuberosity; *ADH*, acromion to distal humerus.
* Implant classification adopted from Werthel et al.[62]

Table VI Humeral lengthening characteristics stratified by global lateralization (M/ML vs. L/HL/VHL) from included studies with classified implants (n = 15)

Parameter	Classification*	Weighted mean (range)	Studies reporting, % (n)	Shoulders reporting, % (n)
AHD	M/ML	23.0 (21.2-24.3)	13.3 (2)	13.2 (139)
AGT	L/HL/VHL	22.8 (20.9-28.6)	26.7 (4)	28.4 (299)
	M/ML	27.9 (23.0-31.0)	26.7 (4)	35.3 (371)
ADT	L/HL/VHL	22.0 (20.3-26.9)	13.3 (2)	13.0 (137)
	M/ML	22.1 (20.4-27.0)	20.0 (3)	14.1 (148)
ADH	L/HL/VHL	20.0 (16.0-22.0)	13.3 (2)	7.9 (83)
	M/ML	17.0 (17.0-17.0)	6.7 (1)	2.2 (23)

M, medialized; *ML*, minimally lateralized; *L*, lateralized; *HL*, highly lateralized; *VHL*, very highly lateralized; *AHD*, acromiohumeral distance; *AGT*, acromion to greater tuberosity; *ADT*, acromion to deltoid tuberosity; *ADH*, acromion to distal humerus.
* Implant classification adopted from Werthel et al.[62]

acromion or scapular spine or nerve injury. Five (5 of 9, 56%) identified an association (Table IX). Of the 6 studies (6 of 22, 27%) that assessed fractures of the acromion and/or scapular spine, 2 identified a positive association with humeral lengthening (2 of 6, 33%), one identified a negative association (1 of 6, 17%), and 3 identified no association (3 of 6, 50%). Stratification by inlay vs. onlay design type and by global lateralization did not reveal a trend. The single study by Zmistowski et al[67] that identified a negative association found that compared to patients without acromial stress symptoms (n = 306), patients with acromial stress fractures (n = 40) had lower ΔAHD (23.4 ± 9.5 vs. 27.6 ± 9.0 mm, P = .009) and ΔADT (9.7 ± 16.6 vs. 21.2 ± 19.2 mm, P < .001). Notably, patients with acromial fractures also trended toward a higher proportion of females (75% vs. 64%, P = .14) and had higher rates of osteoporosis (25% vs. 7%, P < .001). However, increased ΔADT was also associated with lower odds of acromial stress pathology on multivariable analysis, which controlled for both female sex and osteoporosis (OR 0.97 [95% CI 0.95-0.98]; P = .001). The authors hypothesized that patients with less deltoid lengthening would be left at a mechanical disadvantage, requiring significantly greater deltoid force and acromial stress to achieve similar functional goals during rehabilitation compared to patients with greater deltoid lengthening. Furthermore, the authors suggested that patients with fixed pre-existing proximal migration of the humeral head may experience greater acromial stress after RTSA despite minimal humeral lengthening.

Sufficient data were available for comparison of mean humeral lengthening in patients with vs. without fractures of the acromion or scapular spine using meta-analysis. Two patient series were each available for humeral lengthening assessed by the AGT[53,62] and AHD.[15,67] The mean pooled AGT was greater in patients with (n = 33) vs. without (n = 132) a fracture complication (24.3 [95% CI 21.6-26.9] vs. 19.6 [95% CI 16.1-23.0]) (Fig. 3). This equated to a mean difference in the AGT of 4.5 mm (95% CI 0.7-8.3) in patients with vs. without fractures. In contrast, no difference in the mean pooled AHD was found (Fig. 4). Given the similar range of the mean AGT and AHD among included studies (Table IV), all 4 studies suitable for meta-analysis were also pooled (Fig. 5); no difference in the pooled mean lengthening was found.

The single study that assessed the incidence of nerve injury identified a positive association with humeral lengthening. Kim et al[27] reviewed patients who underwent RTSA for cuff tear arthropathy and found greater ΔAGT in

Table VII Percentage of studies reporting a relationship between active ROM and humeral lengthening stratified by measurement method, inlay vs. onlay design, and global prosthesis lateralization

Association with:	Overall (22 studies)	Measurement method (26 series)				Inlay vs. onlay (18 series)			Global lateralization (18 series)	
		AHD	AGT	ADT	ADH	Inlay	Semi-inlay	Onlay	M/ML	L/HL/VHL
Any active ROM										
Yes	57 (8)	33 (1)	71 (5)	60 (3)	50 (1)	83 (5)	33 (1)	60 (3)	75 (6)	50 (3)
No	43 (6)	67 (2)	29 (2)	40 (2)	50 (1)	17 (1)	67 (2)	40 (2)	25 (2)	50 (3)
Not assessed, n	8	2	4	2	1	2	0	2	2	2
Active FE										
Positive	55 (6)	50 (1)	60 (3)	40 (2)	50 (1)	50 (3)	50 (1)	50 (2)	57 (4)	40 (2)
Negative	9 (1)	0 (0)	20 (1)	20 (1)	0 (0)	33 (2)	0 (0)	0 (0)	29 (2)	0 (0)
None	36 (4)	50 (1)	20 (1)	40 (2)	50 (1)	17 (1)	50 (1)	50 (2)	14 (1)	60 (3)
Not assessed, n	3	1	2	0	0	0	1	1	1	1
Active IR										
Positive	33 (3)	0 (0)	25 (1)	50 (1)	50 (1)	0 (0)	0 (0)	60 (3)	0 (0)	50 (3)
None	67 (6)	100 (2)	75 (3)	50 (1)	50 (1)	100 (2)	100 (2)	40 (2)	100 (3)	50 (3)
Not assessed, n	5	1	3	3	0	4	1	0	5	0
Active ER										
Positive	57 (4)	0 (0)	67 (2)	50 (1)	100 (1)	100 (1)	0 (0)	50 (2)	33 (1)	50 (2)
None	43 (3)	100 (2)	33 (1)	50 (1)	0 (0)	0 (0)	100 (2)	50 (2)	67 (2)	50 (2)
Not assessed, n	7	1	4	3	1	5	1	1	5	2
Active abduction										
Positive	25 (1)	0 (0)	0 (0)	50 (1)	0 (0)	0 (0)	0 (0)	33 (1)	0 (0)	25 (1)
None	75 (3)	100 (1)	100 (1)	50 (1)	100 (1)	100 (1)	100 (1)	67 (2)	100 (1)	75 (3)
Not assessed, n	10	2	6	3	1	5	2	2	7	2

ROM, range of motion; *FE*, forward elevation; *IR*, internal rotation; *ER*, external rotation; *AHD*, acromiohumeral distance; *AGT*, acromion to greater tuberosity; *ADT*, acromion to deltoid tuberosity; *ADH*, acromion to distal humerus; *M*, medialized; *ML*, minimally lateralized; *L*, lateralized; *HL*, highly lateralized; *VHL*, very highly lateralized.
Values are % (n).

Table VIII Percentage of studies reporting a relationship between outcome scores and humeral lengthening stratified by measurement method, inlay vs. onlay design, and global prosthesis lateralization

Association with:	Overall (22 studies)	Measurement method (26 series)				Inlay vs. Onlay (18 series)			Global lateralization (18 series)	
		AHD	AGT	ADT	ADH	Inlay	Semi-inlay	Onlay	M/ML	L/HL/VHL
Any outcome score										
Yes	55 (6)	0 (0)	40 (2)	60 (3)	67 (2)	57 (4)	0 (0)	50 (2)	43 (3)	60 (3)
No	45 (5)	100 (1)	60 (3)	40 (2)	33 (1)	43 (3)	100 (1)	50 (2)	57 (4)	40 (2)
Not assessed, n	11	4	6	2	0	1	2	3	3	3
Constant										
Positive	38 (3)	0 (0)	0 (0)	50 (2)	50 (1)	25 (1)	0 (0)	50 (2)	20 (1)	50 (2)
None	63 (5)	100 (1)	100 (3)	50 (2)	50 (1)	75 (3)	100 (1)	50 (2)	80 (4)	50 (2)
Not assessed, n	3	0	4	1	1	3	0	2	2	1
ASES										
Positive	50 (2)	NA	33 (1)	33 (1)	NA	0 (0)	NA	100 (1)	0 (0)	100 (1)
None	50 (2)	NA	67 (2)	67 (2)	NA	100 (4)	NA	0 (0)	100 (4)	0 (0)
Not assessed, n	7	1	4	2	3	3	1	5	3	4
SST										
None	100 (1)	NA	100 (1)	100 (1)	NA	100 (1)	NA	NA	100 (2)	NA
Not assessed, n	10	1	6	4	3	6	1	6	5	5
DASH										
None	100 (1)	NA	NA	NA	100 (1)	100 (1)	NA	NA	100 (1)	NA
Not assessed, n	10	1	7	5	2	6	1	6	6	5
QuickDASH										
None	100 (1)	NA	NA	NA	100 (1)	100 (1)	NA	NA	NA	100 (1)
Not assessed, n	10	1	7	5	2	6	1	6	7	4
EQ-5D										
Positive	100 (1)	NA	NA	NA	100 (1)	100 (1)	NA	NA	NA	100 (1)
Not assessed, n	10	1	7	5	2	6	1	6	7	4

ASES, American Shoulder and Elbow Surgeons Standardized Shoulder Assessment Form; *SST*, Simple Shoulder Test; *DASH*, Disabilities of the Arm, Shoulder, and Hand questionnaire; *EQ-5D*, EuroQol-5 dimensions; *AHD*, acromiohumeral distance; *NA*, not applicable; *AGT*, acromion to greater tuberosity; *ADT*, acromion to deltoid tuberosity; *ADH*, acromion to distal humerus; *M*, medialized; *ML*, minimally lateralized; *L*, lateralized; *HL*, highly lateralized; *VHL*, very highly lateralized.
Values are % (n).

Table IX Percentage of studies reporting a relationship between complications and humeral lengthening stratified by measurement method, inlay vs. onlay design, and global prosthesis lateralization

Association with:	Overall (22 studies)	Measurement method (26 series)				Inlay vs. onlay (18 series)			Global lateralization (18 series)	
		AHD	AGT	ADT	ADH	Inlay	Semi-inlay	Onlay	M/ML	L/HL/VHL
Any complication										
Yes	56 (5)	100 (2)	60 (3)	100 (1)	0 (0)	0 (0)	NA	33 (1)	0 (0)	25 (1)
No	44 (4)	0 (0)	40 (2)	0 (0)	100 (2)	100 (2)	NA	67 (2)	100 (1)	75 (3)
Not assessed, n	13	3	6	6	1	6	3	4	9	4
Fracture*										
Positive	33 (2)	50 (1)	33 (1)	0 (0)	0 (0)	0 (0)	NA	0 (0)	0 (0)	0 (0)
Negative	17 (1)	50 (1)	0 (0)	100 (1)	0 (0)	0 (0)	NA	0 (0)	0 (0)	0 (0)
None	50 (3)	0 (0)	67 (2)	0 (0)	100 (1)	100 (1)	NA	100 (2)	100 (1)	100 (2)
Not assessed, n	3	0	2	0	1	1	0	1	0	2
Nerve injury										
Positive	100 (1)	NA	100 (1)	NA	NA	NA	NA	NA	NA	NA
Not assessed, n	8	2	4	1	2	2	0	3	1	4

AHD, acromiohumeral distance; *NA*, not applicable; *AGT*, acromion to greater tuberosity; *ADT*, acromion to deltoid tuberosity; *ADH*, acromion to distal humerus; *M*, medialized; *ML*, minimally lateralized; *L*, lateralized; *HL*, highly lateralized; *VHL*, very highly lateralized.

Values are % (n).

* Fracture of the acromion or scapular spine.

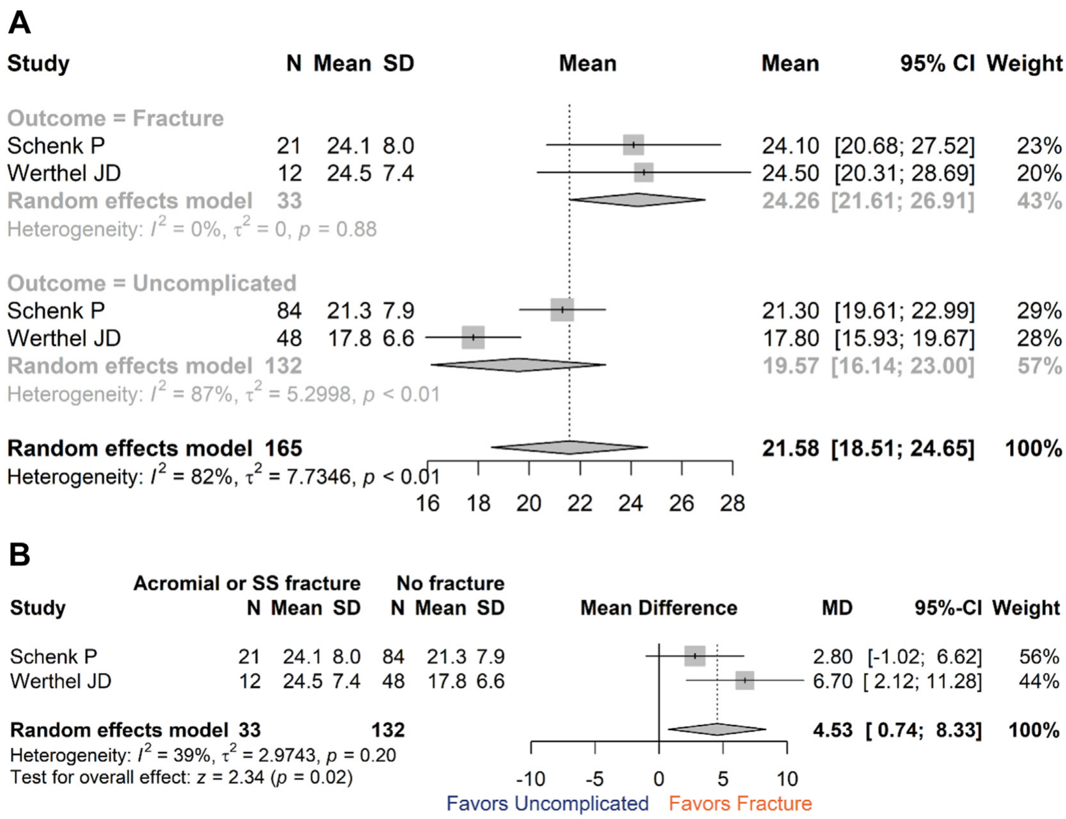

Figure 3 Forest plots depicting (**A**) the mean change in the acromion to greater tuberosity (AGT) distance in patients with vs. without a postoperative fracture of the acromion or scapular spine and (**B**) the mean difference in the AGT between patients with vs. without a fracture of the acromion or scapular spine.

shoulders with (n = 34) vs. without (n = 148) a postoperative neurologic deficit (24.5 ± 9.4 vs. 20.5 ± 8.3 mm, P = .009). In cases of neurologic deficit occurring postoperatively, electromyography (EMG) and nerve conduction velocity (NCV) were performed 4 weeks postoperatively. The involved nerve was diagnosed through physical examination and EMG with NCV. They also reported that 28 patients (82%) with a neurologic deficit had >20 mm of distalization compared to 60 patients (40.5%) in the cohort without a neurologic deficit ($P < .001$). The axillary nerve was injured in 41% of cases.

Discussion

Despite widespread belief that humeral lengthening plays a crucial role in clinical outcomes following RTSA, there is a paucity of clinical evidence supporting this idea. This systematic review investigated the relationship between humeral lengthening and clinical outcomes with further sub-analysis by measurement method and implant lateralization class. Although most included studies reported either a positive or no association between humeral lengthening and clinical outcomes, increased humeral lengthening was associated with poorer forward elevation and increased incidence of acromion fractures in a minority of included studies. We found significant heterogeneity in the measurement method of humeral lengthening and the implants used, which was prohibitive of stratified analysis. The findings of this review demonstrate that the relationship between humeral lengthening and clinical outcomes of RSA is complex and likely multifactorial, and will require future study with large cohorts with a unified assessment of implant positioning and changes in deltoid properties, Among the twenty-two included studies, a total of 4 different measurement techniques of humeral lengthening were employed: ADH (3 of 22, 14%), AHD (5 of 22, 23%), ADT (7 of 22, 32%), and AGT (11 of 22, 50%). Given the heterogeneity of lengthening measurement methodology, reconciling the impact which lengthening has on outcome scores, ROM, and complications across multiple studies becomes dubious when the very anatomic landmarks used to measure lengthening itself differs between studies. For example, because the measurements of AGT and AHD utilize reference points which are relatively proximal on the humerus (the greater tuberosity and head of the humerus respectively), these forms of measurement will be

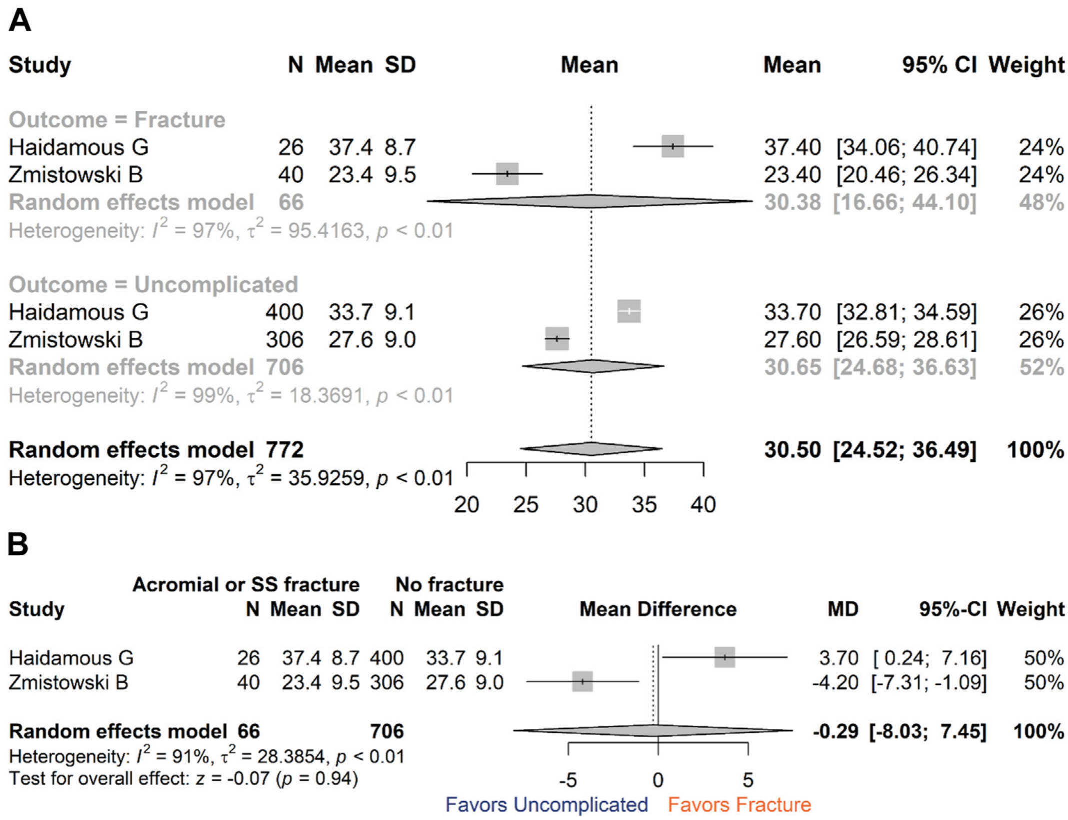

Figure 4 Forest plots depicting (**A**) the mean change in the AHD in patients with vs. without a postoperative fracture of the acromion or scapular spine and (**B**) the mean difference in the AHD between patients with vs. without a fracture of the acromion or scapular spine. *AHD*, acromiohumeral distance.

influenced by the humeral head cut. In contrast, the ADT and ADH measurements are largely independent of this surgical variable as they use the deltoid tuberosity and distal humerus as reference points, which are not influenced by the humeral head cut. However, the ADT and ADH require radiographs of the entire arm, which are often not routinely acquired at many institutions. Furthermore, because the ADT and ADH are longer than the AHD and AGT, the acquired deltas are smaller and thus these measures are less sensitive in detecting humeral lengthening. This point is evidenced by the decrease in the weighted mean lengthening value as the humeral landmark used to measure lengthening became more distal (Table IV). The use of multiple measurement techniques among included studies makes it difficult to compare and understand the true impact of humeral lengthening on outcomes and complications. We recommend that future studies measure lengthening using ADT because of it being easily measured radiographically as compared to ADH and to limit the impact of humeral head osteotomy on measurement as is seen with AGT and AHD. This will eliminate confusion caused by the varying methods of measurement and allow for more accurate comparisons between studies in the future.

Most studies identified a positive relationship between humeral lengthening and FE (6 of 11, 55%; Table VII). This finding is supported by biomechanical studies that found that distalization of the humerus with accompanying tensioning of the deltoid improves the mechanical advantage of the deltoid, leading to improved postoperative FE.[4,22,32] In a computer model study, De Wilde et al[7] demonstrated that elongating the deltoid muscle by 10% resulted in improved shoulder elevation at 90° of abduction in the scapular plane. Jobin et al[22] in their study of 49 patients who underwent RSA for cuff tear arthropathy reported deltoid lengthening that achieved an AGT distance exceeding 38 mm had a 90% positive predictive value of obtaining 135° of active forward elevation, and that deltoid lengthening (average, 21 ± 10 mm) correlated significantly with superior active FE (average = 144° ± 19°; correlation coefficient [R] = 0.66, P = .002). However, our review identified an exception: Sabesan et al[51] reported a weakly negative correlation between increase in AGT and postoperative FE (R = −0.269, P = .045) and a moderately negative correlation between deltoid lengthening and improvement in FE (R = −0.47, P = .031). The authors theorized that this negative association indicates that deltoid lengthening may not be an independent predictor of

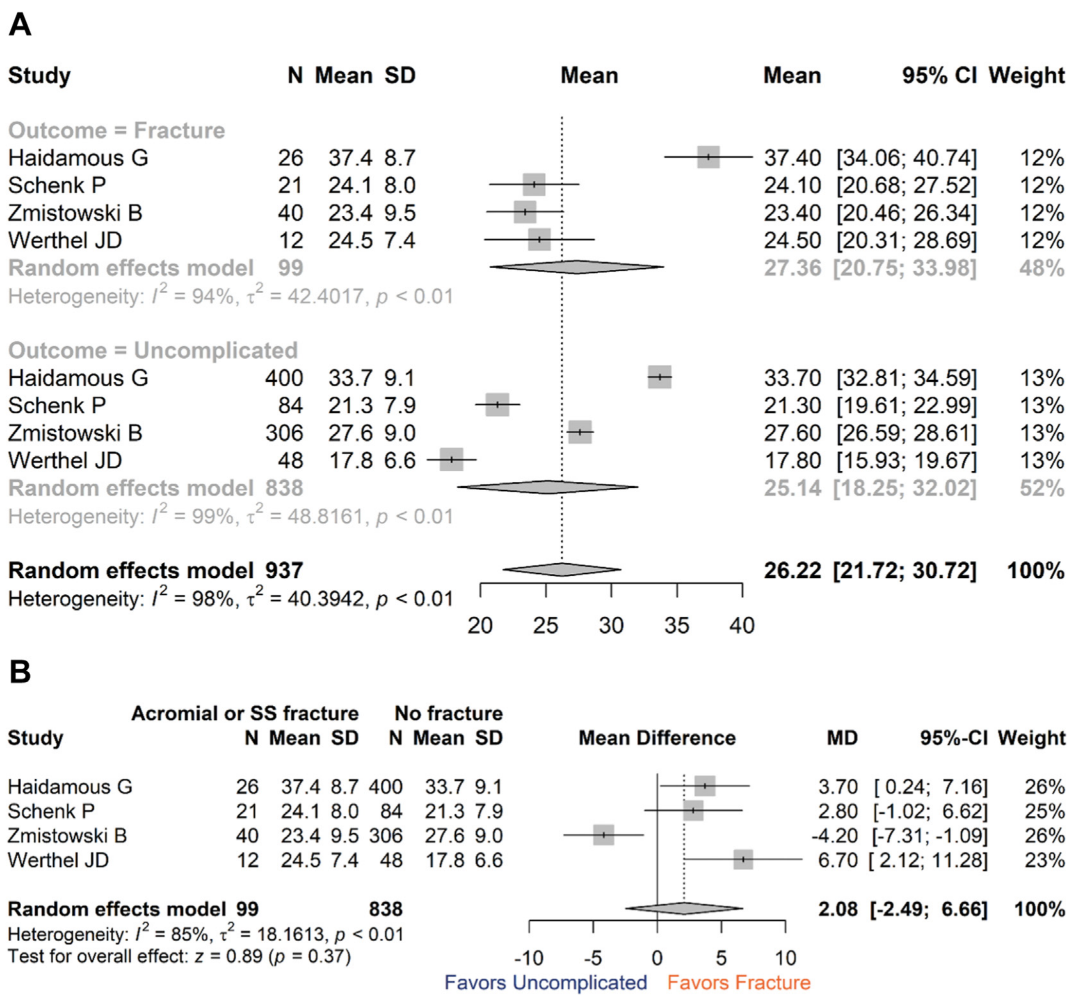

Figure 5 Forest plots depicting (**A**) the mean change in the AGT or AHD in patients with vs. without a postoperative fracture of the acromion or scapular spine and (**B**) the mean difference in the AGT or AHD between patients with vs. without a fracture of the acromion or scapular spine. *AGT*, acromion to greater tuberosity distance; *AHD*, acromiohumeral distance.

postoperative ROM and that there may be a maximum deltoid tensioning limit before there are detrimental effects on function. Although the implants used in Jobin et al[22] and Sabesan et al[51] were different, the design was inlay and globally medialized in both.

Of the 6 studies that evaluated fractures, only 1 found a negative association of humeral lengthening with fracture risk. Zmistowski et al[67] retrospectively reviewed 958 RTSAs performed at a single center with minimum 3 months' follow-up, and reported 40 acromial stress fractures (4.2%) and 61 acromial stress reactions (6.4%). On multivariate analysis, they found increased change in deltoid length (OR 0.97 [95% CI 0.95-0.98]; $P = .001$) to be associated with postoperative acromial stress pathology, and comparison to patients without acromial pathology demonstrated greater COR medialization ($P < .001$), smaller AHD on preoperative ($P = .05$) and postoperative radiographs ($P < .001$), decreased ΔAHD ($P = .01$), decreased postoperative ADT ($P = .01$), decreased ΔADT length ($P < .001$), and decreased ΔCOR offset ($P < .001$), to have greater rates of acromial pathology. The authors postulated that the increased risk of acromial pathology may be due to patients with less deltoid lengthening being left at a mechanical disadvantage, requiring significantly greater deltoid force and thus acromial stress to achieve similar function. Alternatively, Polisetty et al[46] in their review of 47 RTSAs with a postoperative acromion fracture and a control group of 141 RTAs found no differences regarding postoperative degree of inset or offset of humeral implant relative to the anatomic neck, AHD, nor global lateralization class both preoperatively and postoperatively between the fracture and nonfracture groups. Biomechanical studies support the notion that humeral lengthening increases the risk of fracture. Shah et al[56] found that deltoid lengthening >25 mm produced significant strains on the scapular spine and acromion.

Furthermore, the findings of this review clearly show that in addition to humeral lengthening, COR, and implant design play a role in fracture risk. From a biomechanical perspective, COR lateralization may increase deltoid force during overhead motion, thus increasing tension on the acromion and possibly predisposing to acromial and/or scapular spine stress fractures.[29,37,41,64] Wong et al[64] demonstrated that during abduction, glenoid lateralization from 0 to 5 mm and 0 to 10 mm increased maximum acromial stress by 7.7% and 17.2%, respectively. Conversely, Kerrigan et al[26] reported a decrease in acromial strain by 34% with 15 mm lateralization when compared against −5 mm medialization in vitro and Zmistowski et al[67] found a medialized COR to be predisposed to acromial pathology ($P < .001$). Although there are some inconsistencies in biomechanical and clinical findings, the literature seems to indicate both lengthening and COR may influence the risk of acromial and scapular spine fractures, and there may be an interplay between the two. The equipoise in the literature suggests that the relationship between humeral lengthening and the risk of acromial and scapular spine fractures is confounded by other patient- and implant-related factors that need to be accounted for. Although large multicenter studies have been conducted to ascertain predictors of acromial stress fractures, they do not evaluate radiographic factors that characterize humeral lengthening and lateralization.[43,50] Although logistically challenging because of the relative rarity of this complication,[29] determining how humeral lengthening and other implant-related factors influence the risk of acromial fractures likely requires inclusion of thousands of patients from many centers with a variety of radiographic measurements being performed.

Although there is consensus that tensioning the deltoid is critical to outcomes of RSA, it is unclear what proportion of this tension should arise from distalization vs. lateralization. In addition to considering the configuration that minimizes strain on the acromion and scapular spine, the risk of injury to the axillary nerve should also be considered—particularly given the catastrophic consequences in the setting of RSA where shoulder function is reliant on a functioning deltoid. Marion et al[40] conducted a cadaveric study and found that lateralization of the humerus resulted in less stretching of the axillary nerve compared to distalization of the humerus.

We acknowledge there are limitations to this systematic review. These include those inherent to any systematic review, as the analysis of retrospective studies with individual bias will be compounded, the quality of the review is influenced by the quality of the individual studies, and the existence of publication bias. In acknowledgement of some of these limitations, we additionally included the MINORS assessment of bias (Table I).[57] Nevertheless, this review is further limited by the fact that there was no minimum criteria set for level of evidence. Furthermore, follow-up varied between studies, potentially limiting long-term assessment of the influence of humeral lengthening. Although we attempted to use widely accessed databases with broad searches, it remains possible that some articles relevant to this study were not captured. The diversity of implant designs used across the included studies limits the conclusions we can draw about the impact of lengthening on outcomes and complications. Additionally, the variation in radiographic measurement methods used by included studies limits our ability to perform meta-analysis and draw conclusions regarding the relationship between humeral lengthening and postoperative outcomes and complications. Moreover, the varying indications for RTSA used by the included studies such as irreparable rotator cuff tear with pseudoparalysis, glenohumeral arthritis, and cuff tear arthropathy likely may have influenced the relationship between humeral lengthening and clinical outcomes. Although these limitations exist, this review presents a comprehensive review of the reported associations between humeral lengthening and clinical outcomes in the current literature and sheds light on potential areas of need and improvement in future studies.

Conclusion

The relationship between humeral lengthening and clinical outcomes after RSA remains unclear. Although most included studies reported either a positive or no association between humeral lengthening and clinical outcomes, increased lengthening was associated with poorer forward elevation and increased incidence of acromion fractures in a minority of included studies. Limited study inclusion and heterogeneity prohibited identification of trends based on method of measuring humeral lengthening and implant design. A multicenter study assessing humeral lengthening using a standardized protocol is needed to definitively evaluate its influence on outcomes of RSA.

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