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Determination of pre-arthropathy scapular anatomy with a statistical shape model: part I—rotator cuff tear arthropathy

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Hypothesis and background: Rotator cuff tear arthropathy (RCTA) is a pathology characterized by a massive rotator cuff tear combined with acromiohumeral and/or glenohumeral arthritis. The severity of RCTA can be staged according to the Hamada classification. Why RCTA develops in some patients is unknown. Furthermore, in RCTA patients, distinctly different articular damage patterns can develop on the glenoid side as categorized by the Sirveaux classification (glenoid erosion). The goal of this study was to determine whether an association exists between scapular anatomy and RCTA and different severity stages of RCTA, as well as the associated glenoid erosion types.

Methods: A statistical shape model of the scapula was constructed from a data set of 110 computed tomography scans using principal component analysis. Sixty-six patients with degenerative rotator cuff pathology formed the control group. The computed tomography scan images of 89 patients with RCTA were included and grouped according to the Hamada and Sirveaux classifications. A complete 3-dimensional scapular bone model was created, and statistical shape model reconstruction was performed. Next, automated 3-dimensional measurements of glenoid version and inclination, scapular offset, the critical shoulder angle (CSA), the posterior acromial slope (PAS), and the lateral acromial angle (LAA) were performed. All measurements were then compared between controls and RCTA patients.

Results: The control group had a median of 7° of retroversion (variance, 16°), 8° of superior inclination (variance, 19°), and 106 mm of scapular offset (variance, 58 mm). The median CSA, PAS, and LAA were 30° (variance, 14°), 65° (variance, 60°), and 90° (variance, 17°), respectively. In terms of inclination, version, scapular offset, and the PAS, we found no statistically significant differences between the RCTA and control groups. For RCTA patients, the median CSA and median LAA were 32° ($P \leq .01$) and 86° ($P \leq .01$), respectively.

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The ethical committee of the University Hospitals Leuven (Ethische Commissie Onderzoek UZ/KU Leuven) approved this study (no. S58348).

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For all investigated parameters, we did not find any significant difference between the different stages of RCTA. Patients with type E3 erosion had a different pre-arthropathy anatomy with increased retroversion (12°, $P = .006$), an increased CSA (40°, $P \leq .001$), and a reduced LAA (79°, $P \leq .001$).

Discussion: Our results seem to indicate that a 4° more inferiorly tilted and 2° more laterally extended acromion is associated with RCTA. RCTA patients in whom type E3 erosion develops have a distinct pre-arthropathy scapular anatomy with a more laterally extended and more inferiorly tilted acromion and a more retroverted glenoid in comparison with RCTA patients with no erosion. The pre-arthropathy scapular anatomy does not seem to differ between patients with different stages of RCTA.

Level of evidence: Level III; Case-Control Design; Prognosis Study

Keywords: RCTA; glenoid erosion; native anatomy; SSM; glenoid version; CSA; LAA

Rotator cuff tear arthropathy (RCTA) is heterogeneous pathology characterized by a massive rotator cuff tear combined with acromiohumeral and/or glenohumeral arthritis.[12,23] Hamada et al[11] developed a 5-grade classification system for patients with massive rotator cuff tears based on radiographic findings, which was further refined by Walch et al.[34] This grading system is presumed to reflect the temporal evolution of massive rotator cuff tears toward RCTA, in which stages 1 and 2 reflect massive rotator cuff failure and stages 3, 4a, 4b, and 5 reflect RCTA. However, only a subset of patients with stages 1 and 2 undergo a progression toward RCTA.[12,34] Although previous research identified more pronounced rotator cuff failure as a risk factor for this progression,[12,34] why only some patients show progression remains largely unknown. Furthermore, more acromiohumeral arthritis (stage 3) develops in some patients, whereas more glenohumeral arthritis (stage 4a) develops in others. The latter group with glenohumeral arthritis can be further categorized by the different amounts and localization of articular damage on the glenoid side (glenoid erosion). These different types of erosion are typically categorized according to Sirveaux et al[29] into types E0, E1, E2, and E3. Once more, why these different types of RCTA or glenoid erosion develop in patients is not known.

Previous research has focused on the association of scapular anatomy with degenerative shoulder pathology.[13,24] Different scapular morphologic parameters have been investigated in terms of this association, more specifically the extension and tilting of the acromion in the coronal plane—defined by the critical shoulder angle (CSA)[21] and lateral acromial angle (LAA),[3] respectively—as well as the acromial orientation in the sagittal plane—defined by the posterior acromial slope (PAS)[20]—and the orientation of the glenoid in the axial and coronal planes—defined by glenoid version and inclination, respectively. A large lateral extension (large CSA) and downsloping (smaller LAA) of the acromion in the coronal plane seem to be associated with degenerative rotator cuff failure.[3,21,22] The association of less tilting of the acromion in the sagittal plane (PAS),[2] superior glenoid inclination,[14,15] and version[8,15,32,33] with rotator cuff failure seems to be more controversial. On the other hand, a small lateral extension of the acromion combined with a more inferiorly oriented glenoid (small CSA) seems to be correlated with osteoarthritis of the shoulder.[5,21] Furthermore, Meyer et al[20] were able to identify an association between acromial morphology (large PAS) and posterior glenoid erosion in patients with osteoarthritis. The association between glenoid orientation in the axial and coronal planes and osteoarthritis or glenoid erosion is less clear.[17,21,27] As RCTA is often a combination of cuff failure and glenohumeral arthritis, one could ask whether there exists a specific scapular morphology associated with RCTA. The current knowledge about the RCTA patient's scapular anatomy is, however, limited and conflicting. Blonna et al[5] found a correlation between a larger CSA and the severity of RCTA. Heuberer et al[13] reported a more pronounced CSA and less pronounced LAA in RCTA patients compared with patients with osteoarthritis of the shoulder. However, RCTA patients had a less pronounced CSA and more pronounced LAA than patients with rotator cuff failure.

From a methodologic point of view, most available research has used radiographic or computed tomography (CT) scan–based 2-dimensional (2D) measurements in actual patients with disease. Two-dimensional measurements of scapular morphology have been shown to be less reliable than 3-dimensional (3D) measurements.[6,10,19,30] Furthermore, in contrast to premorbid, native measurements, RCTA might have altered these scapular morphologic parameters owing to the disease process.[29] However, recently developed technology can overcome these limitations. A statistical shape model (SSM) makes it possible to (1) reliably perform 3D measurements and (2) reconstruct the pre-arthropathy scapular anatomy.[1,25,26]

Therefore, the primary purpose of this study was to determine whether there is an association between scapular anatomy and RCTA and whether this scapular anatomy is different compared with patients with only rotator cuff failure, using an SSM-based methodology. We hypothesized that patients with RCTA would have a pre-arthropathy scapular anatomy that is comparable to but more pronounced than (large CSA, small LAA) the scapular anatomy associated with rotator cuff failure. Furthermore, we investigated whether there is a different pre-arthropathy scapular morphology between the different stages of RCTA and different types of glenoid erosion associated with RCTA. We hypothesized that a more pronounced pre-arthropathy RCTA anatomy would be associated with a more pronounced stage of RCTA and that patients with glenoid erosion would have a distinct pre-arthropathy scapular anatomy in comparison to patients without glenoid erosion, with the latter corresponding more closely to previously reported features of the scapular anatomy associated with shoulder osteoarthritis.

Materials and methods

SSM and reconstruction

This was a case-controlled, retrospective study. The training data set for the SSM consisted of 110 CT scan images (Definition Flash [Siemens, Erlangen, Germany] with 512 × 512 matrix, full-body field of view, and slice spacing of 0.9 mm or Brightspeed [GE Healthcare, Chicago, IL, USA] with 512 × 512 matrix, 50-cm field of view, and slice spacing of 1.25 mm) from a mixed population of patients with pathology (n = 66, images of patients with different amounts of degenerative rotator cuff pathology) and patients presumably without pathology (n = 44, full-body CT scan images from postmortem investigation at the anatomic pathology department of our hospital) without observable signs of acquired bony anatomic abnormalities or arthropathy as judged by an experienced shoulder surgeon (F.V.) on the 2D CT scan images.

The CT images were segmented using the Mimics Innovation Suite (version 21.0; Materialise, Leuven, Belgium) and converted into smoothed 3D scapular bone models. The smoothing factor was chosen visually, ensuring no relevant anatomic details were lost from the models. Point-to-point correspondences were obtained using an iterative registration procedure. A random instance from the training shape was first chosen as the template. First, rigid registration between each of the training shapes and the template shapes was performed using annotated landmarks and a subsequent iterative closest point algorithm. Second, an open-source nonrigid surface registration algorithm (MeshMonk)[35] was used to establish point-to-point correspondences. These 2 steps were then repeated using the calculated mean shape to remove any bias induced by the randomly chosen template.

The SSM was constructed using principal component analysis.[18] The reconstruction methodology was implemented in the open-source shape modeling framework Scalismo[18] and aimed to reconstruct the native scapular morphology based on the non-diseased parts of the pathologic scapula. The reconstruction algorithm first roughly aligned the shape model to the remaining scapula, after which a Markov chain Monte Carlo algorithm was used to find the optimal pose and shape parameter proposal. The closest-fitting proposal was selected as the final virtual reconstruction[28] (Fig. 1).

Shape model validation

The shape model performance and accuracy of the reconstruction algorithm were evaluated by leave-one-out cross validation. Herein, virtual bone defects of increasing severity (small, medium, and large) were manually defined on the template shape and transferred to each of the training shapes using the established point-to-point correspondences[25] (Fig. 2). The original shape was excluded from the training data set of the SSM during its reconstruction. The overall accuracy of the reconstructed glenoid surface was quantified as the root-mean-square error of the Euclidean distance between the reconstructed glenoid surface and the original glenoid surface. Seven anatomic measurements were used to quantify the reconstructions: version angle, inclination angle, CSA, PAS, LAA, scapular offset, and glenoid center position. These measurements were performed using an in-house script in MATLAB (2019b release; The MathWorks, Natick, MA, USA). For each of these measurements, the difference between the anatomic measurements on the original scapula and the reconstructed scapula was defined as the error. The error in glenoid center position was defined as the Euclidean distance between the original and reconstructed glenoid center points.

RCTA reconstructions

The control group consisted of 66 CT scans (Brightspeed, with 512 × 512 matrix, 50-cm field of view, and slice spacing of 1.25 mm) of the entire scapula from a mixed population of patients with variable amounts of degenerative rotator cuff pathology (mean age, 58 years; 47% male and 53% female patients; 58% right and 42% left shoulders). Degenerative rotator cuff lesions were diagnosed with a combination of anamnesis, clinical investigation, and radiographic investigation (ultrasound and/or arthro-CT scan). Quantification of the magnitude and localization of the degenerative rotator cuff lesions was performed according to Cofield[7] and Teratani,[31] respectively. CT scans were investigated for any signs of arthropathy or acquired bony abnormalities by an experienced shoulder surgeon (F.V.). Eighty-nine patients with different severities of RCTA (mean age, 75 years; 21% male and 79% female patients; 58% right and 42% left shoulders) were included from a CT scan data set (Definition Edge; Siemens; 512 × 512 matrix, maximum field of view of 25 cm, and slice spacing of 0.6 mm) of patients undergoing reverse total shoulder arthroplasty implantation in our institution. RCTA patients were independently classified by 2 observers (F.V. and P.D.) on the basis of the type of glenoid erosion according to Sirveaux et al[29] and the stage of massive rotator cuff failure according to Hamada et al.[12] If the erosion type or Hamada stage was not in agreement between the 2 observers, the images were reinvestigated by the 2 observers together and a consensus was reached.[16] True anteroposterior shoulder radiographs and coronal CT scan views were used for classification. In case of an absent or unclear true anteroposterior view of the shoulder, only the coronal CT scan slices were used for classification. From all the CT scan images of the RCTA patients, a complete 3D scapular bone model was created using Mimics Innovation Suite software (version 20; Materialise). The diseased parts of the glenoid, acromion, and coracoid were removed, and the remaining healthy parts of the scapulae were partitioned and used as the input of the SSM reconstruction algorithm. On the basis of the earlier established point-to-point correspondences, automated 3D measurements were performed on both the control group and all the RCTA patients with reconstruction and without reconstruction: glenoid version and inclination, scapular offset, CSA, PAS and LAA. Definitions of these anatomic measurements are presented in Supplementary Appendix S1. The results for the scapular morphologic parameters were compared

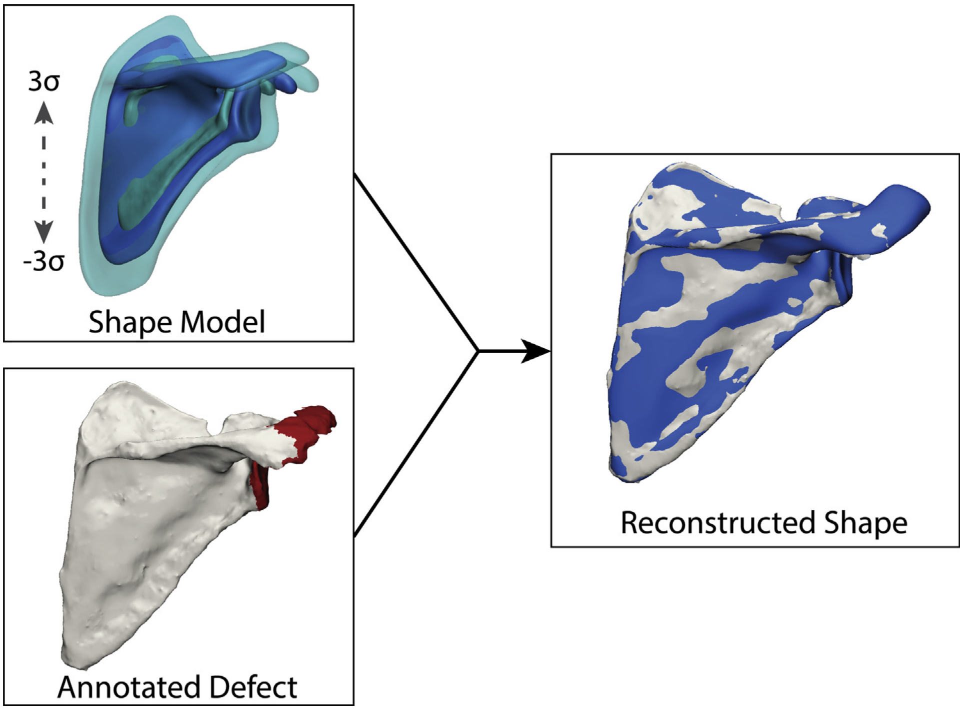


Figure 1 An SSM of the scapula is constructed, containing the morphological variations of the scapula. The diseased area of RCTA scapula is annotated and virtually resected. The remaining healthy parts are used in the reconstruction algorithm to reconstruct the pre-arthropathy scapular anatomy (σ = standard deviation).

between the control group, the RCTA patients as a group, the patients with different types of glenoid erosion, and the patients with different stages of RCTA.

Statistics

The leave-one-out reconstruction errors were found to be non-normally distributed. Consequently, these errors were expressed as median and 25th and 75th percentiles. For the control group, the entire RCTA group, the different erosion types, and the different Hamada stages, 95% confidence intervals were used for descriptive statistics. Because of non-normality, statistically significant differences in the results were evaluated with the nonparametric Kruskal-Wallis test with a significance level of .05. Post hoc analyses were performed using the Mann-Whitney *U* test to compare the results of the different erosion types and Hamada stages interdependently. To correct for type I errors, a

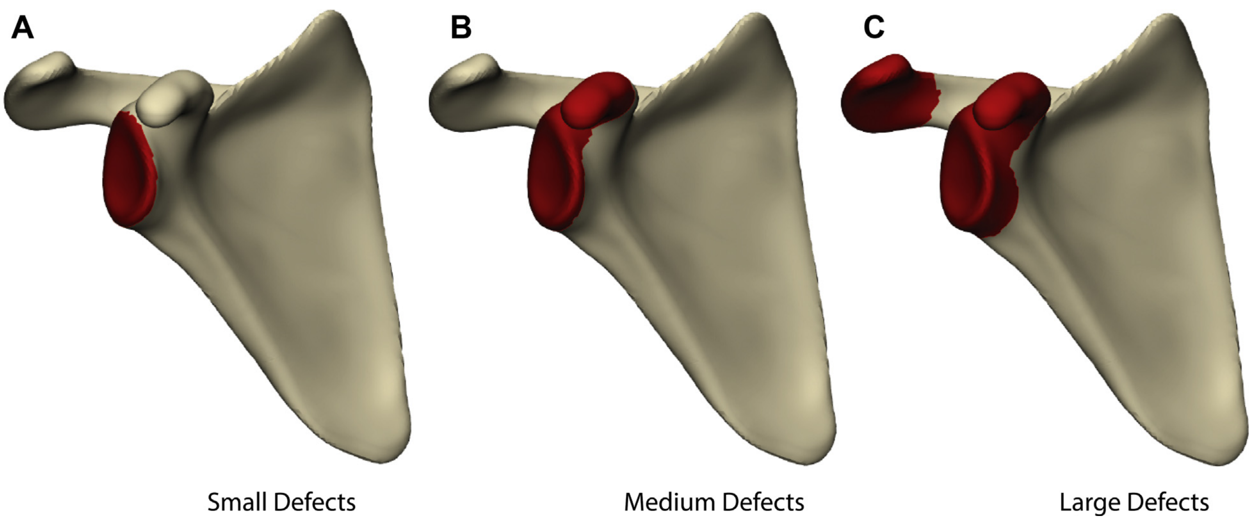
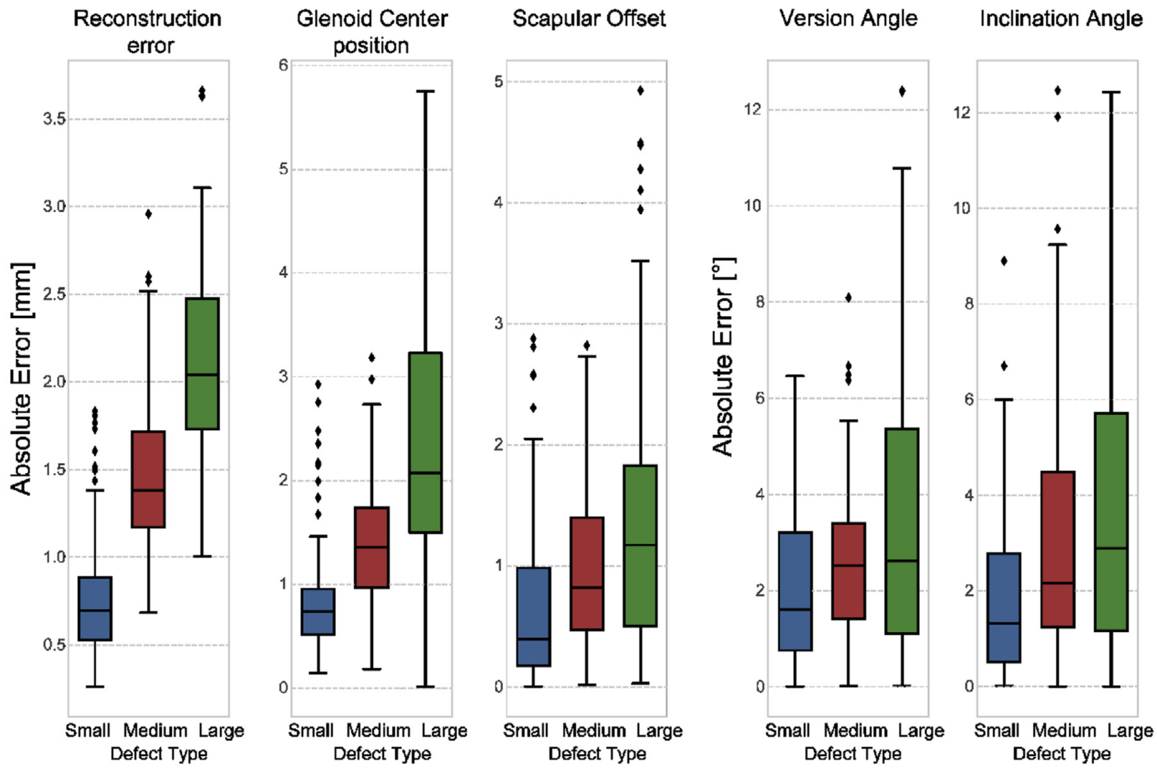


Figure 2 The reconstruction method is validated using artificial defects of three different sizes, analogue to the methodology of Plessers et al.[25]. The defect regions were first annotated on the mean shape (shown) and transferred to each of the training shapes using the established point-to-point correspondences.



	Reconstruction error [mm]	Glenoid Centre [mm]	Scapular Offset [mm]	Version Angle [°]	Inclination Angle [°]
Small	0.7 [0.5, 0.9]	0.7 [0.5, 1.0]	0.4 [0.2, 1.0]	1.6 [0.8, 3.2]	1.3 [0.5, 2.8]
Medium	1.4 [1.2, 1.7]	1.4 [1.0, 1.7]	0.8 [0.5, 1.4]	2.5 [1.4, 3.4]	2.2 [1.3, 4.5]
Large	2.0 [1.7, 2.5]	2.1 [1.6, 3.3]	1.2 [0.5, 1.8]	2.6 [1.1, 5.3]	2.9 [1.2, 5.7]

Figure 3 Boxplot with cross validation results for the reconstruction errors, glenoid center position, and scapular offset position, version angle and inclination angle. Reconstruction errors in the results table are shown as median and [25%, 75%]-confidence intervals.

Bonferroni correction was applied, setting the significance level at .005.

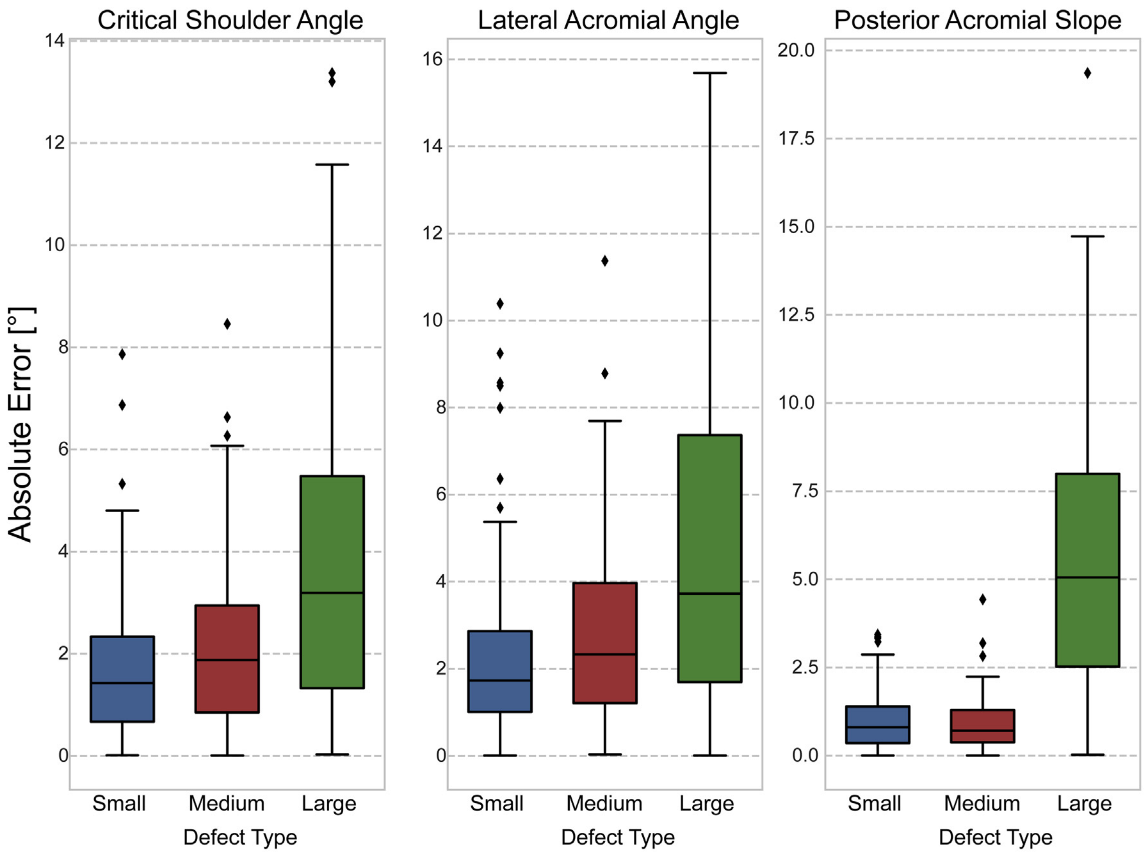
Results

Validation SSM

The error between the original defect surface and reconstructed surface, expressed as the reconstruction error, increased with increasing defect size, with 1-mm median errors for small defects and 2 mm for large defects. In addition, the accuracy of the reconstructed glenoid center worsened with increasing defect size. The glenoid center in the smallest defect types could be predicted with a median error of 1 mm, whereas for medium and large defect types, these errors increased from 1 mm to 2 mm. In contrast, the glenoid offset reconstruction errors remained constant, around 1 mm, for small, medium, and large defects. Defect size was also found to influence the reconstruction of the glenoid angles. For the smallest defects, the associated median error in the version angle equaled 2°; this error increased to 3° for medium and large defects. Similarly, the reconstructed inclination angle errors showed an increase from 2° for small defects to 3° for medium defects and 4° for large defects (Fig. 3). The median accuracy of the reconstructed CSA was 1° for small defects, increasing toward 3° for large defects. The median reconstruction errors for the LAA and PAS were around 1° and 2°, respectively, for small to medium defects; accuracy decreased for large defect sizes. For all parameters, the confidence intervals increased for larger defect sizes. The reconstruction error showed no bias toward either systematic overestimation or systematic underestimation of the scapular parameters (Fig. 4).

RCTA patients vs. control group

The control group consisted of 15 patients with rotator cuff tendinopathy, 9 patients with partial rotator cuff tears, and 42 patients with full-thickness rotator cuff tears (small in 38%, medium in 40%, large in 14%, and massive in 7%; anterosuperior in 17% and posterosuperior in 83%) (Table I). Scapular parameters for the control and RCTA groups are shown in Table I. Compared with the control group, the



	Critical Shoulder Angle [°]	Lateral Acromial Angle [°]	Posterior Acromial Slope [°]
Small	1.3 [0.7, 2.3]	1.7 [1.0, 2.9]	0.8 [0.4, 1.4]
Medium	1.9 [0.9, 3.0]	2.3 [1.2, 4.0]	0.7 [0.4, 1.3]
Large	3.2 [1.3, 5.5]	3.7 [1.7, 7.4]	5.1 [2.5, 8.0]

Figure 4 Boxplot with cross validation results for CSA, LAA and PAS. Reconstruction errors in the results table are shown as median and [25%, 75%]-confidence intervals.

RCTA group showed no difference in version (8° vs. 7° of retroversion, $P = .16$) or inclination (8° superior inclination for both, $P = .80$). The median CSA and LAA for the RCTA group was larger (32° vs. 30°, $P \leq .01$) and smaller (86° vs. 90°, $P \leq .01$), respectively, in comparison with the control group. In terms of the PAS, we found no difference between the 2 groups (64° vs. 65°, $P = .91$). Finally, the scapular offset was different between the 2 groups (102 mm vs. 106 mm, $P \leq .01$).

Type of erosion

Of the 89 RCTA patients, 57 had no erosion (type E0) whereas 11 were classified as having central erosion (type E1); 12, type E2 erosion; and 9, type E3 erosion (Table I). For all erosion types, there were no statistically significant differences compared with the control group or with other erosion types for inclination ($P = .58$), the PAS ($P = .62$), and scapular offset ($P = .02$). For both type E0 and type E1 erosion, we did not find a significant difference in terms of version ($P = .719$ and $P = .652$, respectively), the CSA ($P = .065$ and $P = .337$, respectively), or scapular offset ($P = .046$ and $P = .727$, respectively) compared with the control group. In comparison with the control group, the median LAA was reduced in patients with type E0 and type E1 erosion, measuring 86° vs. 90° ($P \leq .001$) and 85° vs. 90° ($P = .058$), respectively. For type E2 erosion, we found no statistically significant difference in any of the parameters compared with the control group. In comparison with the control group, patients with type E3 erosion had a statistically significantly more pronounced CSA of 40° vs. 30° ($P \leq .001$) and less pronounced LAA of 79° vs. 90° ($P \leq .001$). In terms of the CSA and LAA, differences between type E3 erosion and the other types were observed but did not reach statistical significance except for the comparison with patients without erosion (type E0) (CSA of 40° vs. 31°, $P = .001$, and LAA of 79° vs. 86°, $P = .004$). Median version in patients with type E3 erosion was 12° of retroversion compared with 7° in the control group ($P = .006$), 7° in type E0 patients ($P = .010$), 6° in type E1 patients ($P = .074$), and 8° in type E2 patients ($P = .227$).

Table I Results of pre-arthropathy morphologic scapular parameters for different erosion types and control and RCTA groups

	Mean	Median	Variance	SD	Minimum	Maximum
Inclination, °						
Type E0	8	7	15	4	0	15
Type E1	9	9	16	4	3	15
Type E2	6	6	28	5	−3	15
Type E3	8	10	43	7	−3	18
Control group	8	8	19	4	−3	19
RCTA group	8	8	20	4	−3	18
Version, °						
Type E0	7	7	20	5	−2	18
Type E1	8	6	16	4	1	14
Type E2	10	8	39	6	4	24
Type E3	11	12	15	4	4	15
Control group	7	7	16	4	−2	19
RCTA group	8	8	23	5	−2	24
CSA, °						
Type E0	31	31	13	4	20	40
Type E1	31	31	14	4	25	36
Type E2	33	34	27	5	20	38
Type E3	39	40	37	6	30	49
Control group	30	30	14	4	21	41
RCTA group	32	32	22	5	20	49
PAS, °						
Type E0	65	64	61	8	50	82
Type E1	66	63	37	6	59	74
Type E2	63	65	102	10	51	85
Type E3	60	61	112	11	44	77
Control group	65	65	61	8	46	82
RCTA group	64	64	68	8	44	85
LAA, °						
Type E0	87	86	17	4	79	98
Type E1	87	85	23	5	79	95
Type E2	88	87	24	5	80	94
Type E3	80	79	37	6	69	89
Control group	90	90	17	4	78	100
RCTA group	86	86	24	5	69	88
Scapular offset, mm						
Type E0	104	102	47	7	92	124
Type E1	105	105	41	6	95	116
Type E2	102	104	17	4	94	108
Type E3	100	99	11	3	94	103
Control group	106	106	58	8	93	126
RCTA group	103	102	40	6	92	124

RCTA, rotator cuff tear arthropathy; *SD*, standard deviation; *CSA*, critical shoulder angle; *PAS*, posterior acromial slope; *LAA*, lateral acromial angle.

Stage of RCTA

Patients were divided based on the severity of RCTA according to the Hamada classification (Table II). Types 1 and 2 were taken together as group 1 (16 patients) because they were considered to have massive rotator cuff tears without signs of RCTA. Group 2 consisted of 6 patients with stage 3 massive cuff failure. Groups 3 and 4 comprised 21 patients with type 4a and 44 patients with 4b massive cuff failure, respectively. Group 5 consisted of 2 patients with stage 5. For all investigated parameters, we did not find any significant difference between the different stages of RCTA. For group 4 (stage 4b RCTA), we found a statistically significantly more pronounced CSA of 33° ($P \leq .001$) and less pronounced LAA of 85° ($P \leq .001$) compared with the control group; for the other stages of RCTA, no statistically significant difference was found compared with the control group.

Discussion

The primary purpose of this study was to determine whether there is a scapular anatomy associated with RCTA and whether this scapular anatomy is different compared

Table II Results of pre-arthropathy morphologic scapular parameters for different groups based on Hamada stage

Group	Mean	Median	Variance	SD	Minimum	Maximum
Inclination, °						
1	9	9	16	4	3	15
2	7	7	14	4	3	14
3	7	6	19	4	−3	12
4	8	8	20	4	0	18
5	1	1	34	6	−3	5
Version, °						
1	6	7	17	4	−2	14
2	6	6	20	4	0	12
3	8	6	16	4	1	18
4	8	8	30	5	−2	24
5	11	11	15	4	9	14
CSA, °						
1	32	33	15	4	25	37
2	30	30	8	3	26°	34
3	30	31	14	4	20	36
4	34	33	27	5	20	49
5	36	36	1	1	35	37
PAS, °						
1	66	66	74	9	50	82
2	63	66	115	11	50	74
3	66	66	38	6	53	77
4	63	61	76	9	44	85
5	68	68	22	5	65	71
LAA, °						
1	87	86	32	6	82	101
2	85	85	5	2	92	98
3	89	88	11	3	86	95
4	85	85	24	5	86	111
5	87	87	125	11	85	101
Scapular offset, mm						
1	104	105	82	9	92	124
2	100	99	36	6	95	111
3	103	101	28	5	95	117
4	103	103	33	6	94	116
5	101	101	34	6	97	105

SD, standard deviation; *CSA*, critical shoulder angle; *PAS*, posterior acromial slope; *LAA*, lateral acromial angle.

with the scapular anatomy associated with rotator cuff lesions. To achieve this, a method for virtual reconstruction of the scapula was developed and validated using leave-one-out cross validation. Similar to the studies of Plessers et al[25] and Abler et al,[1] our study found that an SSM is able to reconstruct the scapular morphology with higher accuracy than other reconstruction approaches currently available.[9] Our results in terms of accuracy were in line with those of previous publications showing a median root-mean-square error and median glenoid center point error of 1 mm, with median glenoid inclination, version, CSA, LAA, and PAS errors around 1°-2° for small and medium defects. The median accuracy worsened and its confidence intervals increased for large defect sizes but remained relative small and in line with the findings of previous SSM reconstruction publications.[1,25] The median accuracy of the reconstructed CSA, LAA, and PAS was lower for large defect sizes because these measurements are dependent on the position of the reconstructed acromion, which seems to be less reliable in comparison with glenoid reconstructions. However, only 1 of the 89 RCTA patients in our study had a large defect requiring shape reconstruction of the entire acromion.

Previous studies in the literature found a correlation between a more inferiorly tilted acromion (low LAA), as well as extensive lateral acromial coverage (large CSA), and the occurrence of rotator cuff tears.[3,21,22] When we consider RCTA patients as a homogeneous group, we found a statistically significantly more pronounced CSA (2°) and less pronounced LAA (4°) in patients with RCTA compared with patients with less pronounced rotator cuff failure. This finding is in line with the results of the study of Blonna

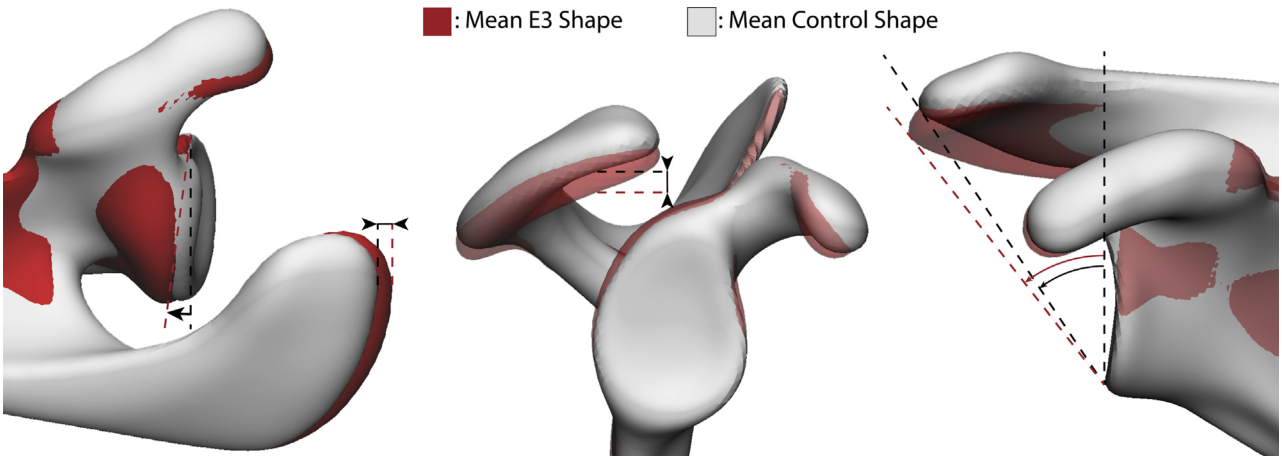


Figure 5 3D images showing the pre-arthropathy scapular anatomy for patients with E3 erosions. The average pre-arthropathy scapular anatomy of patients with E3 erosions is characterized by an increased retroversion, laterally extended and inferiorly tilted acromion.

et al,[5] who found a correlation between an increased CSA and increased severity of rotator cuff failure. There did not seem to be an association between tilting of the acromion in the sagittal plane (PAS) and RCTA development in our study. The relation between glenoid orientation in the coronal plane (inclination) and axial plane (version) and degenerative shoulder pathology is controversial.[4,8,14,32,33] We did not find more pronounced pre-arthropathy glenoid inclination or version in the RCTA patients compared with the control group. Our results seem to indicate that patients with RCTA have a slightly more inferiorly tilted and more laterally extended acromion than patients with smaller amounts of rotator cuff failure. This finding is in line with the current knowledge of rotator cuff failure and the biomechanical impact of extensive acromial coverage and inferior tilting of the acromion.[24] The association between acromial orientation in the sagittal plane or glenoid orientation and RCTA seems to be absent when we consider RCTA patients as a homogeneous group. However, patients with RCTA can be divided into different stages[11,34] using a grading system that is presumed to reflect the temporal evolution of massive rotator cuff tears toward RCTA.

We wanted to investigate whether patients with different stages of RCTA have a different scapular anatomy. Our results did not show any significant difference between the scapular anatomies of the different stages of RCTA. This finding is in line with the hypothesis of the Hamada classification and the clinical findings of long-term observational studies: Patients are able to progress to a higher stage of RCTA, and factors such as the magnitude of rotator cuff failure and time play an important role in RCTA progression.[12,34] RCTA seems to be correlated with a certain acromial morphology (inferior tilt and large lateral extension). On the other hand, we did not find scapular anatomic features that are correlated with the different stages of RCTA. We thus believe that the search for the reasons that more acromiohumeral arthritis (stage 3) develops in some patients with RCTA whereas more glenohumeral arthritis (stage 4a) develops in others should be the subject of future research.

Our second hypothesis was that patients with glenoid erosion associated with RCTA would have a distinct pre-arthropathy scapular anatomy that corresponds more closely to the scapular morphology associated with osteoarthritis. RCTA can be associated with different types of glenoid erosion. Most RCTA patients have no signs of erosion (type E0); others have a more centrally located bone defect (type E1), more superior bone loss (type E2), or total bone loss (type E3).[29] Previous research has found an association between a more horizontal acromial orientation in the sagittal plane (high PAS), glenoid retroversion, and eccentric glenoid erosion in patients with osteoarthritis.[20] We did not find a correlation between the glenoid erosion in RCTA patients and the acromial orientation in the sagittal plane. However, differences in the CSA and LAA were pronounced between RCTA patients with type E3 erosion and RCTA patients without erosion. In terms of glenoid orientation, the median native inclination of type E3 erosion was not statistically significantly different compared with other erosion types or the control group. This finding indicates that the differences in the CSA and LAA can largely be attributed to the acromial morphology in terms of height, lateral extension, and tilting.[4] In terms of version, the difference between patients with type E3 erosion and controls or patients without erosion reached a clinically meaningful 5°, although this was statistically found to be borderline nonsignificant. Our results seem to indicate that patients with type E3 erosion have a distinct pre-arthropathy scapular anatomy with a more laterally extended and more inferiorly tilted acromion, thereby possibly leading to more expressed rotator cuff failure. This more expressed rotator cuff failure could be the cause of the more expressed bone erosion (type E3). The role of the more expressed pre-arthropathy glenoid retroversion associated with type E3 erosion should be the subject of further research (Fig. 5).

The strength of this study is the state-of-the-art SSM-based reconstruction technique, allowing automated 3D measurements of the pre-arthropathy scapular anatomy. Our SSM was based on a large data set of 110 CT scan images from a mixed population of pathologic and non-pathologic scapulae without signs of arthropathy or acquired bony abnormalities. We pragmatically opted to use this population because it could be the best representation for the scapular parameters of the entire population. The finding that our SSM CT data had a normal distribution for all the anatomic scapular parameters further reinforced this hypothesis. The entire methodology was performed in a fully automated way, excluding any observer dependency.

This study has some weaknesses. First, classification of glenoid erosion according to Sirveaux et al[29] and Hamada et al[11,12] may be challenging.[16] As a mitigation, we had 2 experienced shoulder surgeons classify all shoulders separately and enforced consensus in case of disagreement. Second, the control data set was not a data set of normal patients but rather a mixed population made up of patients with degenerative rotator cuff pathology but without signs of arthropathy on CT scans. We used this control data set because our main research question was to investigate whether there is a difference in the scapular anatomy associated with RCTA, different stages of RCTA, and rotator cuff failure. Third, the RCTA results are from a mixed population of RCTA patients with a relatively low amount of type E2 and type E3 erosion and Hamada grade 3 patients. Some of our results reached significance despite this small subpopulation, whereas for other data (eg, version), this was not the case. Future research with a larger sample size should therefore be undertaken to confirm the relationship specifically between increased pre-arthropathy glenoid retroversion and type E3 erosion. Fourth, despite removal of those regions likely affected by secondary morphologic changes due to the arthropathy prior to the SSM reconstruction, our study design does not allow us to fully rule out a possible bias on the native reconstructions of RCTA as a consequence of secondary changes in terms of the morphology outside of the removed regions. As a result, further prospective, longitudinal research is warranted to further clarify the role of the native morphology in the etiology of RCTA. In line with this limitation, we opted to not reconstruct CT scans of RCTA patients without any signs of bony erosion or alterations. The number of RCTA patients without reconstruction, however, was low (15%).

Another limitation concerns the SSM reconstruction and measurement methodology. Accuracy for most of the scapular parameters was found to decrease in large defect sizes, thereby also having a possible effect on the validity of our results in patients with larger defect sizes specifically and, consequently, in the subgroups containing a possibly larger number of patients with these large defect sizes (eg, type E3 erosion). However, the vast majority of the defects included in this study were only small to medium (only 1 patient was considered to have a large defect). Therefore, we believe that this has no major influence on the obtained results for the RCTA patients as a group. Furthermore, for the subgroup with the possibly largest defect sizes (type E3 erosion), the differences for the reported parameters (version, CSA, and LAA) compared with the control group and type E0 group were higher than the median reconstruction error of the SSM for the large defect sizes, so we believe that our conclusion for type E3 erosion is valid. We assumed that RCTA deformation was limited to the area near the glenoid cavity, inferior surface of the acromion, and coracoid surface in contact with the humeral head and therefore removed only these parts for fitting, but RCTA might extend to other regions. This could lead to larger inaccuracies in SSM reconstructions because of fitting to possibly unhealthy regions. However, small variations in the scapular shape will have only a minor influence on the results. A final limitation concerns the CSA and LAA measurements. They were originally defined as 2D measurements based on the upper and lower poles of the glenoid. We opted here to instead use 3D measurements based on the glenoid plane. However, one has to be aware that direct comparisons with data on the CSA and LAA in the available literature are hampered by this choice, as the glenoid plane typically does not go through the upper pole of the glenoid.

Conclusion

To our knowledge, this is the first study to describe the scapular anatomy of RCTA patients without underlying assumptions concerning the pathologic anatomy being altered due to the disease process. Although our study reports systematic and statistically significant differences between RCTA patients and the control group, these remain small in terms of clinical significance. Further prospective, longitudinal research is required to further clarify its role in the etiology of RCTA. Patients with pronounced glenoid erosion (type E3) seem to have a specific pre-arthropathy scapular anatomy with a more laterally extended and inferiorly tilted acromion, combined with a more retroverted glenoid, than RCTA patients with no erosion.

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Supplementary data

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