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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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Title: Determination of pre-arthropathy scapular anatomy with a statistical shape model – Part I: Rotator Cuff Tear arthropathy.

Running Title: Scapular anatomy in RCTA

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Determination of pre-arthropathy scapular anatomy with a statistical shape model – Part I: Rotator Cuff Tear arthropathy

Abstract:

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. Severity of RCTA can be staged according to Hamada. It is unknown why some patients develop RCTA. Furthermore, RCTA patients can develop distinctly different articular damage patterns on the glenoid side as categorized by Sirveaux (glenoid erosion). The goal of this study was to determine if there exists an association between scapular anatomy and RCTA, different severity stages of RCTA and their associated glenoid erosion types.

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

Results: The control group had a median of 7° retroversion (variance 16°), 8° superior inclination (variance 19°) and 106mm scapular offset (variance of 58mm). The median CSA, PAS and LAA was 30° (variance 14°), 65° (variance 60°) and 90° (variance 17°) respectively. In terms of inclination, version, scapular offset and PAS we found no statistically significant

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difference between the RCTA and the control group. For RCTA patients, median CSA and LAA was 32° ($p \leq 0.01$) and 86° ($p \leq 0.01$) respectively. For all investigated parameters, we did not find any significant difference between the different stages of RCTA. Patients with an E3 type of erosion had a different pre-arthropathy anatomy with increased retroversion (12° , $p = 0.006$), CSA (40° , $p \leq 0.001$), and reduced LAA of 79° ($p \leq 0.001$).

Discussion: Our results seems to indicate that a 4° more inferiorly tilted and 2° more lateral extended acromion is associated with RCTA. RCTA patients who develop an E3 type of erosion 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. There does not seem to be a different pre-arthropathy scapular anatomy between patients with different stages of RCTA.

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

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

Rotator Cuff Tear Arthropathy (RCTA) is heterogeneous pathology characterized by a massive rotator cuff tear combined with acromiohumeral and/or glenohumeral arthritis^{23 12}. Hamada et al developed a five-grade classification system of patients with massive rotator cuff tears based on radiographic findings¹¹, which was further refined by Walch et al³⁴. This grading system is presumed to reflect the temporal evolution of massive rotator cuff tears towards RCTA, where stage 1 and 2 reflect massive rotator cuff failure and stages 3, 4a, 4b and 5 RCTA. However,

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only a subset of patients with stage 1 and 2 undergo a progression towards RCTA^{12 34}. Although previous research identified more pronounced rotator cuff failure as risk factors for this progression^{12 34}, it remains largely unknown why only some patients progress. Furthermore, some patients develop more acromiohumeral arthritis (stage 3) and others more glenohumeral arthritis (stage 4a). The latter group with glenohumeral arthritis can be further categorized by different amounts and localization of articular damage on the glenoid side (glenoid erosion). These different types of erosions are typically categorized according to Sirveaux et al in E0, E1, E2 and E3 types of erosions²⁹. It is -once more- not known why patients develop these different types of RCTA or glenoid erosions.

Previous research already focused on the association of scapular anatomy with degenerative shoulder pathology^{24 13}. 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 the lateral acromion angle (LAA)³ respectively - as well as the acromial orientation in the sagittal plane - defined by the posterior acromial slope (PAS)²⁰ - and orientation of the glenoid in the axial and coronal plane - defined by glenoid version and inclination. A large lateral extension (large CSA) and down-sloping (smaller LAA) of the acromion in the coronal plane seems to be associated with degenerative rotator cuff failure^{22 21 3}. The association of less tilting of the acromion in the sagittal plane (PAS)², superior glenoid inclination^{14 15} and version^{15 32 33 8} 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^{21 5}. Furthermore, Meyer et al were able to identify an

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association between acromial morphology (large PAS) and posterior glenoid erosion in patients with osteoarthritis. The association between glenoid orientation in the axial and coronal plane and osteoarthritis or glenoid erosion is less clear^{21 17 27}. As RCTA is often a combination of cuff failure and glenohumeral arthritis, one could ask if 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 have found a correlation between a larger CSA and the severity of RCTA⁵. Heuberger et al found a more pronounced CSA and less pronounced LAA in RCTA patients compared to patients with osteoarthritis of the shoulder. However, RCTA patients had a less pronounced CSA and more pronounced LAA compared to patients with rotator cuff failure¹³.

From a methodological point of view, most available research used radiographic or computed tomography (CT) scan based 2D measurements on actual diseased patients. 2D measurements of scapular morphology have been shown to be less reliable in comparison with three-dimensional (3D) measurements^{6 19 10 30}. Furthermore, in contrast with pre-morbid, native measurements, RCTA might have altered these scapular morphologic parameters due to the disease process²⁹. However, recent 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^{25 26 1}. Therefore, the primary purpose of this study was to determine if there is an association between scapular anatomy and RCTA and if this scapular anatomy is different compared to patients with only rotator cuff failure, using a SSM based methodology. We hypothesized that patients with RCTA have a pre-arthropathy scapular anatomy that is comparable - but more pronounced (large CSA, small LAA) - to the scapular

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anatomy associated with rotator cuff failure. Furthermore, we investigated if there is a different pre-arthropathy scapular morphology between the different stages of RCTA and different types of glenoid erosions associated with RCTA. We hypothesized that a more pronounced pre-arthropathy RCTA anatomy is associated with a more pronounced stage of RCTA and that patient with glenoid erosions have a distinct pre-arthropathy scapular anatomy in comparison to patients without glenoid erosions, with the latter corresponding more closely to previously reported features of the scapular anatomy associated with shoulder osteoarthritis.

Materials and Methods

This is a case-controlled, retrospective study. The ethical committee of the University Hospitals Leuven (S58348) approved this study.

Statistical shape model and reconstruction

The training dataset for the SSM consisted of 110 CT scan images (Siemens Definition Flash, Erlangen, Germany; matrix 512 x512, full body field of view, slice spacing 0.9mm and Brightspeed, GE Healthcare, Chicago, IL, USA, matrix 512 x 512, 50cm field of view and slice spacing of 1.25mm) from a mixed population of pathologic (n= 66, patients with different amounts of degenerative rotator cuff pathology) and presumably non-pathologic patients (n= 44, full body CT scan images from post-mortem investigation at the anatomical pathology department of our hospital) without observable signs of acquired bony anatomical abnormalities or arthropathy as judged by an experienced shoulder surgeon (FV) on the 2D CT-scan images. The CT images were segmented using Mimics Innovation Suite (v21.0; Materialise, Leuven,

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Belgium) and converted to 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. Secondly, an open-source non-rigid surface registration algorithm (MeshMonk)³⁵ was then used to establish point-to-point correspondences. These two steps were then repeated using the calculated mean shape to remove any bias induced by the randomly chosen template. The SSM was then constructed using principal component analysis¹⁸. The reconstruction methodology was implemented in the open-source shape modelling framework Scalismo¹⁸ and aims to reconstruct the native scapular morphology based on the non-diseased parts of the pathologic scapula. The reconstruction algorithm first roughly aligns the shape model to the remaining scapula, after which a Markov chain Monte Carlo algorithm is used to find the optimal pose and shape parameter proposal. The closest fitting proposal was selected as the final virtual reconstruction²⁸ (Figure 1).

Shape model validation

The shape model performance and accuracy of the reconstruction algorithm was 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 correspondences²⁵ (Fig 2). The original shape was excluded from the training dataset of the SSM during its reconstruction. The overall accuracy of the reconstructed glenoid surface was quantified as the root-mean-square error

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(RMSE) 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; The Mathworks Inc., Natick, MA, USA). For each of these measurements, the difference between the anatomical measurements on the original and the reconstructed scapula was defined as the error. The error on the glenoid center position was defined as the Euclidean distance between the original and reconstructed glenoid center point.

RCTA reconstructions

The ‘control’ group consisted of sixty-six CT scans (Brightspeed, GE Healthcare, Chicago, IL, USA; matrix 512 x 512, 50cm field of view and slice spacing of 1.25mm) of the entire scapula from a mixed population of patients with variable amount of degenerative rotator cuff pathology (mean age: 58years, 47% male/ 53% female, 58% right shoulders/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 Cofield⁷ and Teratani³¹ 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: 75years, 21% male/79% female, 58% right shoulders/42% left shoulders) were included from a CT scan (Siemens Definition Edge, Forchheim, Germany; matrix 512 x 512, max 25 field of view and slice spacing of 0.6mm) dataset of patient undergoing reverse total shoulder arthroplasty implantation in our institution.

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RCTA patients were classified independently by two observers (F.V. and P.D.) based on 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. In case the erosion type or Hamada stage was not in agreement between the two observers, the images were reinvestigated by the two observers together and a consensus was reached ¹⁶. The true anteroposterior shoulder radiographs and coronal CT scan views were used for classification. In case of absent or unclear true anteroposterior view of the shoulder, only 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 with Mimics Innovation Suite software (v20; Materialise, Leuven, Belgium). 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. Based on the earlier established point-to-point correspondences, automated 3D measurements were performed on both the control group and all the reconstructed and non-reconstructed RCTA patients: glenoid version and inclination, scapular offset, CSA, PAS and LAA (The definition of these anatomic measurements can be found in supplementary material 1). The results for the scapular morphologic parameters were compared between the control group, the RCTA patients as a group, the patients with different types of glenoid erosions 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 using their median and 25-75% percentiles. For the control group, entire RCTA group, the different erosion types and the different Hamada stages a 95% confidence interval was used for the descriptive statistics. Because of non-normality,

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statistical differences for the results were evaluated with non-parametric Kruskal-Wallis tests with significance level 0.05. Post hoc analyses were performed using Mann-Whitney U tests to compare the results of the different erosion types and Hamada stages interdependently. To correct for type I errors a Bonferroni correction was applied setting the significance level at 0.005.

Results

Validation SSM

The error between the original defect surface and reconstructed surface, expressed as the reconstruction error, increases with increasing defect size with 1 mm median errors for small defects, to 2mm for large defects. In addition, the accuracy of the reconstructed glenoid center worsens with increasing defect sizes. The glenoid center in the smallest defect types can be predicted with a median error of 1mm, whereas for medium and large defect types these errors increase from 1 mm to 2mm, respectively. In contrast, the glenoid offset reconstruction errors remained constant around 1mm 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 on the version angle equals 2°, these errors increase to 3° for medium and large defects. Similarly, for the reconstructed inclination angle errors, where the error increase from 2° to 3° and 4° for small, medium and large defects respectively (Fig 3). The median accuracy of the reconstructed CSA was 1° for small defects increasing towards 3° for large defects. Median reconstruction error for LAA and PAS was around 1° and 2° for small to medium defects, accuracy decreased for large defect sizes. For all parameters, the confidence intervals increase

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for larger defect sizes. The reconstruction error had no bias towards either systematic over- or underestimation of the scapular parameters. (Fig 4).

RCTA patients vs control group (Table 1)

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 (38% small tears, 40% medium tears, 14% large tears, 7% massive tears, 17% anterosuperior tears and 83% posterolateral tears). Scapular parameters for the control and RCTA group can be found in table 1. Compared to the control group, the RCTA group had no difference in version (8° vs 7° retroversion, $p = 0.16$) or inclination (both 8° superior inclination, $p = 0.80$). The median CSA and LAA for the RCTA patient was respectively larger and smaller in comparison with the control group (32° vs 30° , $p \leq 0.01$ and 86° vs 90° , $p \leq 0.01$). In terms of PAS we found no difference between both groups (64° vs 65° , $p = 0.91$). Finally, also the scapular offset was different between both groups (102mm vs 106mm, $p \leq 0.01$).

Type of erosion (Table 1)

Of the 89 RCTA patients, 57 had no erosion (E0), 11 patients were classified as having a central erosion (E1), 12 patients as having an E2 and nine patients had an E3 type of erosion. For all erosion types there was no statistically significant differences with the control group or with other erosion types for inclination ($p = 0.58$), PAS ($p = 0.62$) and scapular offset ($p = 0.02$). For both the E0 and E1 types of erosion, we did not find a significant difference in terms of version ($p = 0.719$ and $p = 0.652$ respectively), CSA ($p = 0.065$ and $p = 0.337$ respectively) or scapular offset ($p = 0.046$ and $p = 0.727$ respectively) with the control group. In comparison with the

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control group, median LAA was reduced for patients with E0 and E1 type of erosions, measuring 86° vs 90° ($p \leq 0.001$) and 85° vs 90° ($p = 0.058$) respectively. For E2 types of erosion, we found no statistical difference in any of the parameters with the control group. In comparison with the control group, patients with E3 types of erosion had a statistically significant more pronounced CSA of 40° vs 30° ($p \leq 0.001$) and less pronounced LAA of 79° vs 90° ($p \leq 0.001$). In terms of LAA and CSA differences between E3 types and other erosion types were observed, but did not reach statistical significance except vs. patients without erosions (E0 types); CSA (40° vs 31°, $p = 0.001$) and LAA (79° vs 86°, $p = 0.004$). Median version for E3 types was 12° of retroversion compared with 7° for the control group ($p = 0.006$), 7° for E0 types ($p = 0.010$), 6° for E1 types ($p = 0.074$) and 8° for E2 types ($p = 0.227$).

Stage of RCTA (Table 2)

Patients were divided based on the severity of RCTA according to Hamada et al. Type 1 and 2 were taken together as group 1 (16 patients) because they were considered as massive rotator cuff tears without signs of RCTA. Group 2 consisted of six patients with stage 3 massive cuff failure. Group 3 and 4 were 21 patients with type 4a and 44 with 4b massive cuff failure respectively. Group 5 were two patients with Grade 5. For all investigated parameters, we did not find any significant difference between the different stages of RCTA. For group four (stage 4b RCTA) we found a statistically significantly more pronounced CSA of 33° ($p \leq 0.001$) and less pronounced LAA 85° ($p \leq 0.001$) compared with the control group, for the other stages of RCTA no statistically significant difference was found with the control group.

Discussion.

The primary purpose of this study is to determine if there is, a scapular anatomy associated with RCTA and if this scapular anatomy is different compared to the scapular anatomy associated with rotator cuff lesions. For this, a method for the virtual reconstruction of the scapula was developed and validated using leave-one-out cross-validation. Similar to the studies of Plessers et al and Abler et al we found that SSM is able to reconstruct the scapular morphology with higher accuracy than other reconstruction approaches currently available^{1 25 9}. Our results in terms of accuracy were in line with previous publications showing a median RMS error and median glenoid center point error of 1 mm, median glenoid inclination, version, CSA, LAA and PAS error 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 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 one of the 89 RCTA patients in our study had a thus-sized defect requiring shape reconstruction of the entire acromion.

Previous literature found a correlation between a more inferiorly tilted acromion (low LAA), a large lateral acromial cover (large CSA) and the occurrence of rotator cuff tears^{3 21 22 21}. When we consider RCTA patients as a homogenous group we found a statistically significant more pronounced CSA (2°) and less pronounced LAA (4°) for RCTA patients in comparison with patients with less pronounced rotator cuff failure. This is in line with the study of Blonna et al

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who found a correlation between increased CSA and increased severity of rotator cuff failure⁵. There does not seem to be an association in our study between tilting of the acromion in the sagittal plane (PAS) and RCTA development. The relation between glenoid orientation in the coronal plane (inclination) and axial plane (version) and degenerative shoulder pathology is controversial^{8 14 32 4 33}. We did not find a more pronounced pre-arthropathy glenoid inclination or version for the RCTA patients compared with our control group. Our results seem to indicate that patients with RCTA have a slightly more inferiorly tilted and larger laterally extended acromial compared to patients with smaller amounts of rotator cuff failure. This finding is in line with the current knowledge of rotator cuff failure and biomechanical impact of a large acromial cover and inferior tilting of the acromion²⁴. The association between acromial orientation in the sagittal plan or glenoid orientation and RCTA seems to be absent when we consider RCTA patients as a homogenous group. However, patients with RCTA can be divided in different stages^{11 34}. This grading system is presumed to reflect the temporal evolution of massive rotator cuff tears towards RCTA. We wanted to investigate if 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 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 like magnitude of rotator cuff failure and time play an important role in RCTA progression^{12 34}. RCTA seems to be correlated with a certain acromion 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 reasons why patients develop more acromiohumeral arthritis

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(stage 3) and others more glenohumeral arthritis (stage 4a) of RCTA should be the subject of future research.

Our second hypothesis was that patients with glenoid erosions associated with RCTA 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 erosions. Most RCTA patients have no signs of erosion (E0), others have a more centrally located bone defect (E1), more superior bone loss (E2) or total bone loss (E3) ²⁹. Previous research 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 erosions in RCTA patients and the acromial orientation in the sagittal plane. However, differences in CSA and LAA were pronounced between RCTA patients with E3 type of erosion and RCTA patients without erosions. In terms of glenoid orientation, median native inclination of E3 types of erosions was not statistically significant different compared with other erosion types or the control group. This indicates that the difference in 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 E3 types of erosions and controls or patients without erosion reached a clinically meaningful 5°, although this was statistically found to be borderline non-significant. Our results seem to indicate that patients with E3 type of erosions 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 erosions (E3 type). The role of the more

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expressed pre-arthropathy glenoid retroversion associated with E3 erosions should be 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 scapula without signs of arthropathy or acquired bony abnormalities. We pragmatically opted to use this population because this 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 anatomical 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 erosions according to Sirveaux et al and Hamada et al may be challenging¹⁶. As a mitigation, we had two experienced shoulder surgeons classify all shoulders separately and enforced consensus in case of disagreement.

Second, the control dataset was not a dataset of normal patients but a mixed population made up of patients with degenerative rotator cuff pathology but without signs of arthropathy on CT-scan.

We used this control dataset because our main research question was to investigate if there is a difference in the scapular anatomy associated with RCTA, different stages of RCTA and rotator cuff failure. Third, RCTA results are from a mixed population of RCTA patients with a relatively low amount of E2 and E3 erosions types and Hamada grade three patients. Some of our results reached significance despite this small subpopulation whereas for others (like 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 E3 type

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of erosions. 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 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 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 erosions or alterations. The number of non-reconstructed RCTA patients, however, was low (15%). Another limitation concerns the SSM reconstruction and measurement methodology. Accuracy for most of the scapular parameters was found to decrease for large defect sizes. Thereby also having a possible effect on the validity of our results for patients with larger defect sizes specifically and consequently also the subgroups containing a possibly larger number of patients with these large defect sizes (e.g. E3 erosions). However, the vast majority of the defects included in this study were only small to medium (only one patient was believed 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 (E3 erosions) the differences for the reported parameters (version, CSA and LAA) with the control group and E0 group was higher than the median reconstruction error of the SSM for the large defect sizes, so we believe that our conclusion for E3 erosions 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 on the scapula shape will only have a

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minor influence on the results. A final limitation concerns CSA and LAA measurements. They were originally defined as 2D measurements based on the upper and lower pole 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 the available literature for CSA and LAA 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 that describes 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 difference 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 (E3) seem to have a specific prearthropath scapular anatomy with a more laterally extended and inferiorly tilted acromion, combined with a more retroverted glenoid in comparison with RCTA patients with no erosion.

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Table legends

Table 1. Results for the pre-arthropathy morphologic scapular parameters for the different erosion types, control group and RCTA group (CSA= critical shoulder angle, PAS = posterior acromial slope, LAA= Lateral acromion angle).

Table 2: Results for the pre-arthropathy morphologic scapular parameters for the different groups of Hamada stages (CSA= critical shoulder angle, PAS = posterior acromial slope, LAA= Lateral acromion angle)..

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

	group	Mean	Median	Variance	Std. Deviation	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	1	104mm	105mm	82mm	9mm	92mm	124mm
	2	100mm	99mm	36mm	6mm	95mm	111mm
	3	103mm	101mm	28mm	5mm	95mm	117mm
	4	103mm	103mm	33mm	6mm	94mm	116mm
	5	101mm	101mm	34mm	6mm	97mm	105mm

	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]

a) Small Defects

b) Medium Defects

c) Large Defects

	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]