Is there an association between the individual anatomy of the scapula and the development of rotator cuff tears or osteoarthritis of the glenohumeral joint?

A RADIOLOGICAL STUDY OF THE CRITICAL SHOULDER ANGLE

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We hypothesised that a large acromial cover with an upwardly tilted glenoid fossa would be associated with degenerative rotator cuff tears (RCTs), and conversely, that a short acromion with an inferiorly inclined glenoid would be associated with glenohumeral osteoarthritis (OA). This hypothesis was tested using a new radiological parameter, the critical shoulder angle (CSA), which combines the measurements of inclination of the glenoid and the lateral extension of the acromion (the acromion index).

The CSA was measured on standardised radiographs of three groups: 1) a control group of 94 asymptomatic shoulders with normal rotator cuffs and no OA; 2) a group of 102 shoulders with MRI-documented full-thickness RCTs without OA; and 3) a group of 102 shoulders with primary OA and no RCTs noted during total shoulder replacement. The mean CSA was 33.1° (26.8° to 38.6°) in the control group, 38.0° (29.5° to 43.5°) in the RCT group and 28.1° (18.6° to 35.8°) in the OA group. Of patients with a CSA > 35°, 84% were in the RCT group and of those with a CSA < 30°, 93% were in the OA group.

We therefore concluded that primary glenohumeral OA is associated with significantly smaller degenerative RCTs with significantly larger CSAs than asymptomatic shoulders without these pathologies. These findings suggest that individual quantitative anatomy may imply biomechanics that are likely to induce specific types of degenerative joint disorders.

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Both rotator cuff tears (RCTs) and osteo arthritis (OA) of the glenohumeral joint are common.[1,2] However, OA is rarely associated with RCTs, whereas RCTs are seldom associated with relevant osteo-arthritic changes and then only late in the course of the disease.[3-6] The aetiology of these degenerative pathologies is multifactorial and remains poorly understood. Among many factors, the quantitative individual anatomy of the scapula has been found to be associated with the occurrence of RCTs. Increased upward tilt of the glenoid is associated with an increased risk of tears of the supraspinatus tendon,[7-9] and increased retroversion of the glenoid is associated with tears of the anterior cuff, whereas increased anteversion is linked with tears of the posterior cuff.[9]

The association of lateral extension of the acromion (the acromion index) with the development of RCTs and OA has been investigated.[10] Nyffeler et al[10] postulated that a large index results in a more vertical orientation of the force vector of the middle fibres of the deltoid, which will tend to pull the humeral head upwards, requiring the supraspinatus to exert a greater horizontal force to stabilise the centre of rotation during active abduction.[11] On the other hand, in shoulders with a short acromion the compressive component of the deltoid would become dominant and synergistic with the supraspinatus vector. This should increase the load on the surface of the glenohumeral joint, thereby favouring degenerative wear and leading to OA, whereas the stress on the rotator cuff would be reduced. Whereas a high acromion index was strongly associated with degenerative RCTs, Nyffeler et al[10] reported no significant correlation between a low index and OA of the glenohumeral joint. However, OA is often associated with flattening of the humeral head and progressive wear of the glenoid.[3] Both of these degenerative changes misleadingly increase the acromion index. Furthermore, the index does not account for the tilt of the glenoid fossa. We therefore developed a radiological parameter that takes into account both the tilt of the

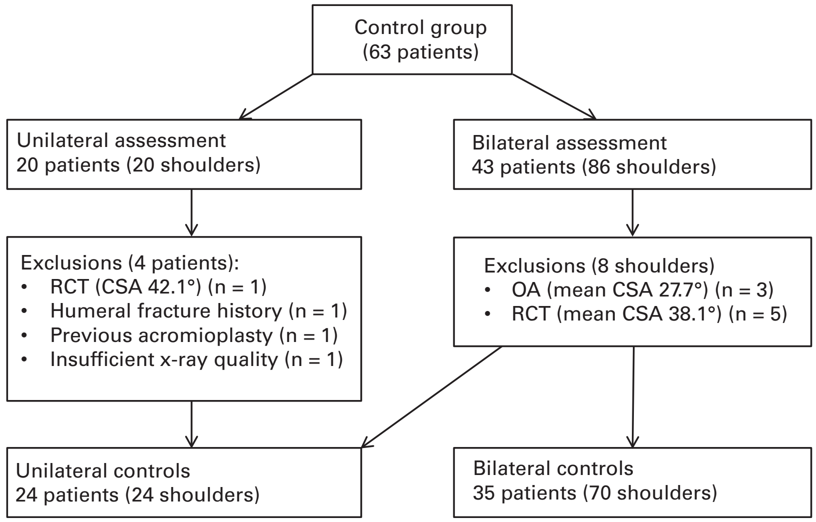

Fig. 1

Flow chart showing the formation of the control group of shoulders (RCT, rotator cuff tear; CSA, critical shoulder angle; OA, osteoarthritis).

glenoid in the frontal plane and the acromion index, but eliminates the influence of degenerative changes of the humerus.

We hypothesised that this new parameter would correlate with wear of either the rotator cuff tendons or the articular cartilage of the glenohumeral joint. Therefore, we called it the critical shoulder angle (CSA). This study was performed to verify a possible association between the CSA and either RCTs or primary OA of the glenohumeral joint.

Patients and Methods

After obtaining ethical approval, we retrospectively identified 279 patients of our institution to be included in this study. They gave informed consent, and after examination were divided into three groups.

The control group comprised 63 consecutive patients who were being treated for an orthopaedic problem not involving the shoulder. Only those patients with asymptomatic shoulders and no history of previous surgery or pathology involving the shoulder were included. An independent musculoskeletal radiologist performed ultrasonography on each shoulder to assess the integrity of the rotator cuff. Then conventional radiographs were taken and evaluated for degenerative changes in the glenohumeral joint. Shoulders with evidence of partial or full-thickness tears of the rotator cuff or signs of OA according to Samilson and Prieto[12] were excluded. This left 59 patients (30 female and 29 male) with a mean age of 65.9 years (60 to 73). There were 24 patients (13 women and 11 men) with unilateral and 35 patients (17 women and 18 men) with bilateral measurements of the shoulder, resulting in a total control group of 94 shoulders (Fig. 1).

The RCT group comprised a consecutive series of 124 patients who between January 2010 and October 2010 underwent unilateral arthroscopic repair of the rotator cuff for a full-thickness tear of at least the supraspinatus tendon, with available pre-operative true anteroposterior radiographs. Patients with an acromio-humeral distance of < 7 mm and hence possible wear of the superior glenoid rim were excluded, as were those with a traumatic RCT, inflammatory disease or previous surgery. This left a total of 102 patients (34 women and 68 men) with a mean age of 58.1 years (44 to 77).

The OA group consisted of patients with primary OA of the glenohumeral joint treated with conventional total shoulder replacement (TSR) between March 2003 and May 2011; in whom the integrity of the rotator cuff was confirmed at operation. There were 92 patients (52 women and 40 men) with a mean age of 68.7 years (47 to 85). Of these, ten patients (six women and four men) had undergone bilateral TSR, thereby producing a total of 102 shoulders in 92 patients. A pre-operative CT scan was routinely performed to determine retroversion of the glenoid according to Friedman et al,[13] as well as to classify the morphology of the glenoid using the method described by Walch et al.[14] Only patients without previous surgery but with pre-operative true anteroposterior radiographs were included. There was no patient with an acromio-humeral distance of < 8 mm in this group, and wear of the inferior or superior glenoid rim was not observed.

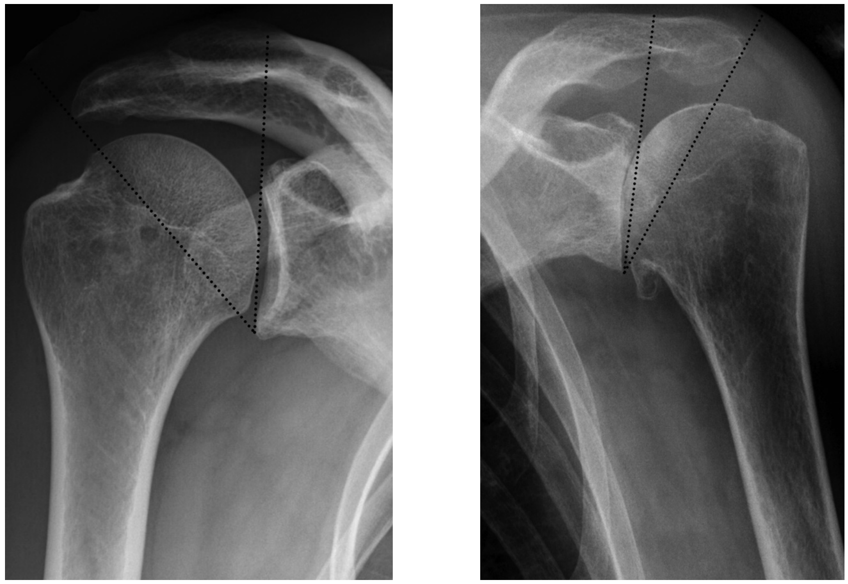

Fig. 2a Fig. 2b

Sample radiographs of glenohumeral joints showing the assessment of the critical shoulder angle (CSA; measured between a line connecting the inferior with the superior border of the glenoid fossa and another connecting the inferior border of the glenoid with the most inferolateral point of the acromion), a) in a shoulder with a full-thickness tear of supraspinatus tendon (CSA 43°) and b) in a shoulder with osteoarthritis and an intact rotator cuff (CSA 22°).

All measurements were taken electronically on radiographs displayed on a PACS workstation (Cerner Corp., Kansas City, Missouri). Two independent assessors (BKM, SB) assessed the CSA on standardised true anteroposterior radiographs made with the arm in the neutral position (Fig. 2). The angle was formed by a line connecting the superior and inferior bony margins of the glenoid and a line drawn from the inferior bony margin of the glenoid to the most lateral border of the acromion. After a delay of three months, one reader assessed the CSA again in all shoulders of the control group to determine interobserver reliability.

Evaluation of the measurement technique. Theoretically, the projected CSA could vary according to the position of the scapula. For this study, only true anteroposterior (AP) radiographs with visible joint space and only minimal overlap between the posterior and anterior rim of the glenoid were included. This was facilitated by the fact that AP radiographs of the glenohumeral joint are routinely taken under fluoroscopic control in our hospital. In order to quantify the potential error in measurement of the CSA as a function of the projection of the scapula, we measured it on radiographs from a previous experimental study, which had been carried out to study the influence of the position of the scapula on parameters other than the CSA.[15] In this study, two dried left human scapulae were fixed in a device that allowed incremental internal and external rotation and flexion and extension of the scapula. The position of the scapula was changed in increments of 10°, 20°, 30°, 40° extension or flexion and internal or external rotation, and in combinations of both. Conventional AP radiographs were taken in each position.

Statistical analysis. Statistical analysis was carried out by a biostatistician. A one-way analysis of variance (ANOVA), followed by the Bonferroni *post hoc* test, was performed to compare the three groups. Statistical significance was set at $p < 0.05$. Mean differences between groups were presented with 95% confidence intervals (CI). In order to assess the inter- and intra-observer reliability of the proposed measurement method, the Bland–Altman method was used.[16] Intraclass correlations were computed using the absolute agreement definition in a two-way mixed model. Logistic regression and receiver-operating characteristic (ROC) analyses were performed to determine cut-off values and assess sensitivity and specificity.

Results

The analysis of the influence of rotation on the CSA is shown in Figures 3 and 4. These show that a malrotation of > 20° is easily identified by the oval shape of the glenoid. No such radiographs were present in this study. The experimental analysis of the dependence of the CSA on rotation shows that it increases slightly with internal rotation and decreases slightly with external rotation. These changes do not exceed 2° for rotation and/or flexion of up to 20° and are therefore considered irrelevant. If rotational errors exceed 20°, a reproducible demarcation of the superior and inferior bony margins of the glenoid becomes almost impossible. Corresponding observations were made for

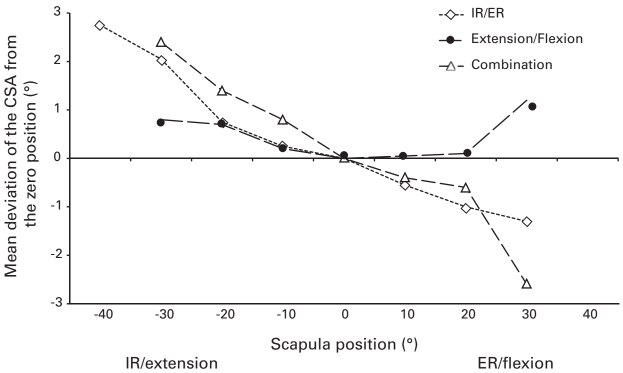

Fig. 3

Graph showing the influence of altered scapular position on the projected critical shoulder angle (CSA) assessed on two cadaver scapulae. The *x*-axis shows the dimensions of rotation in extension or internal rotation (IR) as negative and flexion or external rotation (ER) as positive values. The *y*-axis shows the mean deviation in degrees from the neutral position (Combination, progressive rotation from 40° IR and extension to 40° ER and flexion).

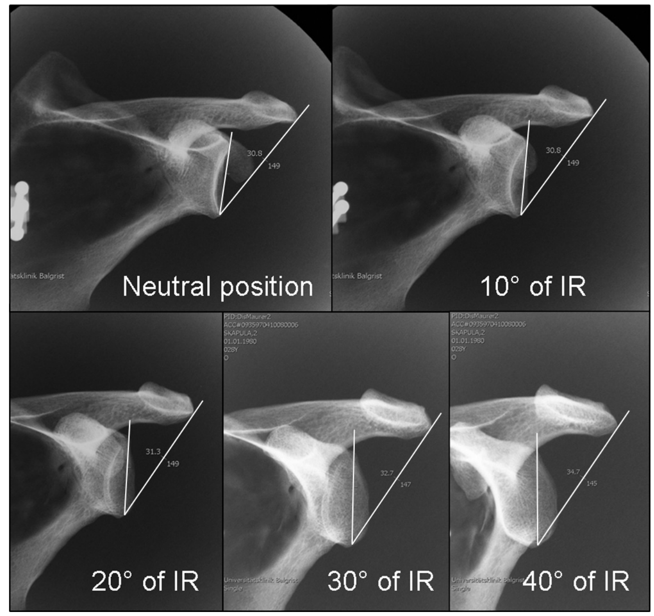

Fig. 4

Sample radiographs showing the influence of progressive internal rotation (IR) on the radiological appearance of the glenoid. Analogous changes are found with progressive external rotation. A malrotation > 20° leads to a substantial overlap between the anterior and posterior glenoid rims, and the reproducibility of the critical shoulder angle (CSA) decreases. Patients with such radiographs were not compatible with inclusion in the study, nor would we accept such radiographs in clinical practice. However, below this range the CSA is almost stable and the influence of rotation is negligible.

combined flexion/extension and rotational malpositions. A consistently reproducible assessment of the CSA yielding variability ≤ 2° was documented for malrotations up to 20° of internal rotation or extension and 20° of external rotation or flexion. Larger positional errors, however, are excluded by the inclusion criteria applied in this study.

The data are summarised in Table I. ANOVA followed by the Bonferroni *post hoc* test demonstrated a significant difference ($p < 0.0001$) of 5° (95% CI 4.0 to 5.9) between the control and RCT groups and 5° (95% CI 4.1 to 6.0) between the control and OA groups.

Within the control group, the mean CSA of the unilateral healthy shoulders (n = 59) was 33.3° (SD 2.2; 28.8° to 38.6°). Of the 35 patients with bilateral healthy shoulders, the mean intra-individual difference in CSA was 1.2° (SD 1.1; 0.1° to 4.2°) ($p = 0.36$). The mean intra-individual difference in CSA within the eight patients with unilateral shoulder disease was 3.5° (SD 1.9; 0.4° to 6.3°) ($p = 0.22$).

The mean retroversion of the glenoid in the OA group was 9° (-8° to 22°). There were 56 type A1[14] (55%), 24 type A2 (23.5%), 14 type B1 (13.7%) and eight type B2 (7.8%) glenoids. With a mean of 21.1° (18° to 22°), retroversion was most pronounced in type B2, compared to with 11.5° (6° to 20°) in type B1, 9.4° (-2° to 19°) in type A2 and 6.4° (-8° to 15°) in type A1. However, there was no significant difference in the mean CSA of different glenoid morphologies (type A1 27.8°; type A2 28.1°; type B1 28.1° and type B2 29.8°; range of p-values 0.13 to 0.7).

Logistic regression and ROC curve analysis determined the cut-off value for discriminating between the control and RCT groups for the CSA as 35.3°. The area under the curve (AUC) was excellent at 0.92, indicating that the CSA is a valuable measure for discriminating between the RCT and control groups. This is also reflected in the sensitivity and specificity of respectively 0.82 and 0.92. The power of the CSA to discriminate between the OA and the control groups was also excellent. At a cut-off of 29.9° the CSA exhibited an AUC of 0.90 and a sensitivity and specificity of 0.78 and 0.97, respectively.

Based on these findings, CSA values were classified into three grades. In grade 1 the CSA is < 30°: 80 shoulders (93%) in this group were osteo-arthritic. In grade 2 the CSA is between 30° and 35°, which is considered 'normal'; 78 of these shoulders (70%) were in the control group, 18 (16%) in the OA group and 14 (14%) in the RCT group. For grade 3 the CSA is > 35°: 84 (84%) were in the RCT group and only four (4%) in the OA group.

Interobserver reliability was excellent, with a bias between the two readers of 0° (limits of agreement -2° to +2°; Fig. 5). Intra-observer reliability showed a minimal bias of -0.21° (SD 1.1) (limits of agreement -2° to +2°).

Discussion

There are many theories to explain the aetiology of degeneration of the rotator cuff. Armstrong[17] was among the first to suggest a mechanical conflict between the acromion and the supraspinatus tendon as the cause of the so-called supraspinatus syndrome. This theory was later supported and popularised by Neer.[18] Based on cadaveric dissection and intra-operative observation, he introduced the term impingement syndrome to describe mechanical conflict

Table I. Synopsis of the overall dataset

Characteristic*	Group Control (n = 94)	RCT (n = 102)	OA (n = 102)
Mean age (yrs) (SD; range)	65.9 (3.2; 60 to 73)	58.1 (8.5; 44 to 77)	68.7 (8.9; 47 to 85)
Mean CSA (°) (SD; range)	33.1 (2.1; 26.8 to 38.6)	38.0 (2.8; 29.5 to 43.5)	28.1 (3.3; 18.6 to 35.8)

* CSA, critical shoulder angle
† RCT, rotator cuff tear; OA, osteoarthritis

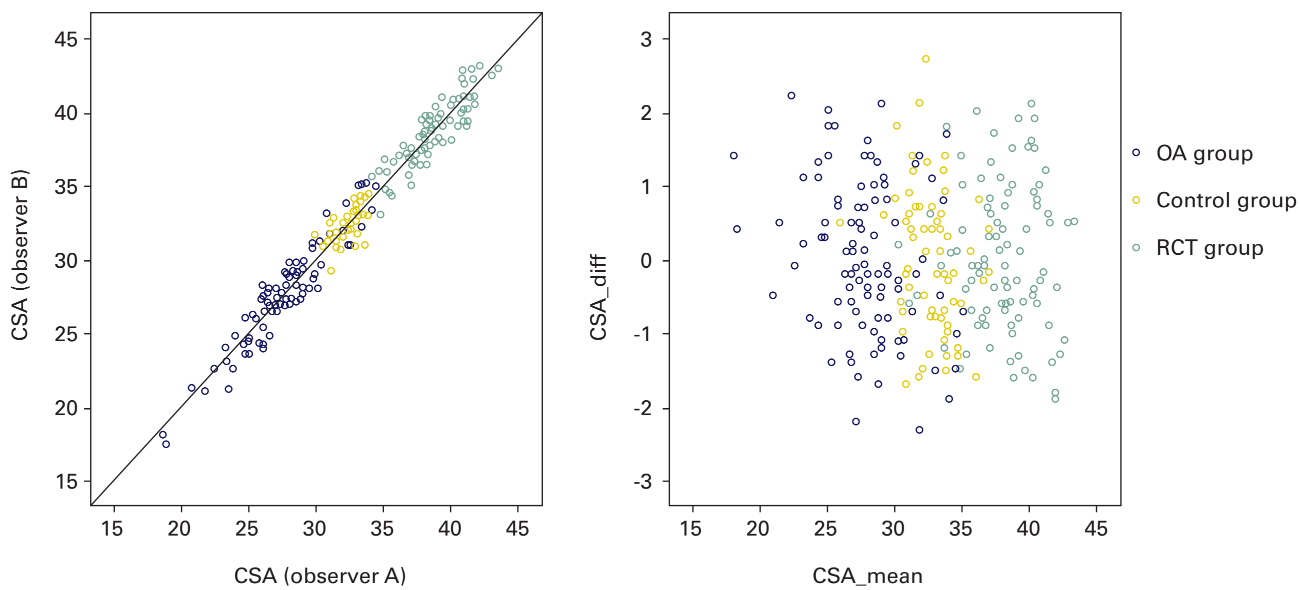

Fig. 5

Correlation graph (left) between the critical shoulder angle (CSA) measured by the two observers and inter-rater reliability demonstrated with the Bland–Altman method (right) (OA osteoarthritis; RCT, rotator cuff tear).

between the anterior acromion and the rotator cuff. He hypothesised that bursal-side lesions were caused by this conflict and attributed 95% of all RCTs to the pathological shape of the anterior acromion.[18,19] Bigliani, Morrison and April[20] identified three distinct acromial shapes that were more or less likely to be associated with RCTs. A higher prevalence of RCTs was then found in shoulders with an increased anterior projection and a flatter slope of the acromion on lateral radiographs, as well as with a decreased lateral acromial angle.[21-23] All these morphological changes were felt to reduce the size of the supraspinatus outlet, thereby leading to increased pressure or friction on the rotator cuff tendons and progressive tearing. Hyvönen, Lohi and Jalovaara,[24] however, showed that elimination of acromial compression by open acromioplasty did not prevent further RCTs, thereby challenging the key role of subacromial impingement in the degenerative process. Other authors strongly contested this concept of pathogenesis and showed that the acromial changes are most likely to be a consequence and not the cause of an RCT; several studies have since shown that the acromial changes are not congenital but progressively acquired, and most likely to be related to traction.[25-29]

More recently, an upward-facing glenoid, as well as glenoid version, has been found to be an additional risk factor for RCTs.[7-9] Nyffeler et al[10] introduced the concept of the acromion index, hypothesising that changes in acromial shape may alter the biomechanics of the glenohumeral joint in such a way as to explain excessive loading of the rotator cuff muscles as well as high compressive loads on the articular cartilage.

Although a high acromion index was strongly associated with degenerative RCTs, there was only a trend for an association between a short acromion and glenohumeral OA.

Based on an analysis of true AP radiographs, we observed that progressive degeneration of the glenohumeral joint often modifies the acromion index, making the difference between individuals with OA and those without less evident (Fig. 6). We therefore introduced the concept of the CSA, which quantifies the extent of acromial cover without being influenced by a flattening of the humeral head or excessive bony erosion of the posterior

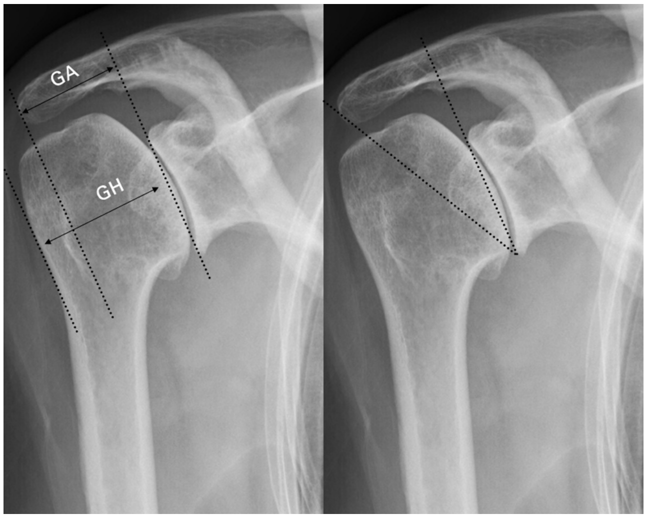

Fig. 6

Radiographs of the right glenohumeral joint in a patient with osteoarthritis and intra-operatively confirmed integrity of the rotator cuff. Owing to considerable flattening of the humeral head, the acromial index (GA/GH) was misleadingly high (0.76), whereas the critical shoulder angle (CSA; 27°) stayed within the range of the mean CSA of the osteoarthritis group.

glenoid, both of which are typically found in glenohumeral OA.[3-5] In addition, the CSA reflects not only acromial cover but also the inclination of the glenoid, integrating both risk factors into one biomechanical parameter.

This study demonstrates that the CSA is a simple, highly reproducible tool which is insensitive to minor malrotations of the scapula. If the joint line is visible without excessive overlap of the anterior and posterior glenoid rims, the CSA is reproducible. Our data indicate that the glenohumeral joint of a patient of approximately 65 years of age without OA or a RCT is characterised by a CSA between 30° and 35°. Angles > 35° are associated with a high prevalence of RCTs, whereas shoulders with a CSA of < 30° are likely to be osteo-arthritic. These observations are compatible with the concept that a healthy shoulder undergoes balanced mechanical loading. If the anatomical configuration diverts from normal, as measured with the CSA, overload of the cartilage may result in OA of the glenohumeral joint, or overload of the supraspinatus may lead to a tear of its tendon. However, these assumptions cannot be confirmed by the design of this study.

The strength of this study is that it uses large sample sizes with consecutive series of patients. Its limitation is the case–control design, with collection of data retrospectively and the use of both shoulders, especially in the control group. One could argue that the likelihood of similar ranges of variables in both shoulders is increased, thereby potentially reducing the power of the sample size. However, owing to the large difference in CSA between the RCT and OA groups (with a mean of 10°), this bias is unlikely to jeopardise the findings. Additionally, our data would remain statistically significant even if only unilateral shoulders were used in the control group. Furthermore, the patient selection excluded those with secondary wear of the inferior or superior rim of the glenoid, which could – albeit minimally – alter the value of the CSA.

This study introduces a new radiological index which combines the acromion index and the inclination of the glenoid fossa. Our data demonstrate that primary glenohumeral OA is associated with significantly smaller and degenerative RCTs with significantly larger CSAs than asymptomatic shoulders, which have neither OA nor degenerative rotator cuff disease. Further studies, however, should determine whether this association has a cause and effect relationship. Such studies appear justified because the CSA would be a biomechanical parameter that could potentially be addressed surgically.

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