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Premorbid glenoid anatomy reconstruction from contralateral shoulder 3-dimensional measurements: a computed tomography scan analysis of 260 shoulders

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Background: Total shoulder arthroplasty (TSA) aims to reconstruct the premorbid anatomy of a pathologic shoulder. A healthy contralateral shoulder could be useful as a template in planning TSA. The symmetry between the left and right shoulders in healthy patients remains to be proved. The purpose of this study was to compare the 3-dimensional anatomy of the glenoid between sides in a healthy population.

Methods: A multinational computed tomography scan database was retrospectively reviewed for all healthy bilateral shoulders in patients aged between 18 and 50 years. One hundred thirty pairs of healthy shoulder computed tomography scans were analyzed, and glenoid version, inclination, width, and height, as well as glenoid lateral offset and scapula lateral offset, were measured. All anatomic measures were computed with Blueprint, validated 3-dimensional planning software. The intraclass correlation coefficient was determined for each measure between left and right shoulders. The minimal detectable change (MDC) was calculated using the following formula: MDC $= \sqrt{2} \times 1.96 \times$ Standard error of measurement.

Results: The comparison between 130 pairs of healthy scapulae showed statistically significant differences in absolute values between right and left glenoid version ($-5.3°$ vs. $-4.6°$, $P < .01$), inclination ($8.4°$ vs. $9.3°$, $P < .01$), and width (25.6 mm vs. 25.4 mm, $P < .01$), as well as scapula offset (105.8 mm vs. 106.2 mm, $P < .01$). Glenoid height was comparable between right and left shoulders (33.3 mm vs. 33.3 mm, $P = .9$). The differences between the means were always inferior to the MDC regarding glenoid version, inclination, height, and width, as well as scapula offset. Very strong intraclass correlation coefficients between the left and right shoulders were found for all evaluated paired measures.

Conclusion: Healthy contralateral scapulae are highly reliable to predict inclination, height, width, and scapula offset and are reliable to predict version of a given scapula. Paired right and left scapulae were not statistically symmetrical regarding mean glenoid version, inclination, and width, as well as scapula offset. Nevertheless, the reported differences were not higher than the MDC for this cohort, confirming that healthy contralateral shoulders can be a useful template in TSA preoperative planning.

Conseil d'Orientation Scientifique Ramsay Santé Comité d'Ethique approved this study (institutional review board no. COS-RGDS-2023-05-008-WALCH-G), and all patients provided informed consent.

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Several studies have demonstrated that preoperative planning using 3-dimensional (3D) computed tomography (CT) images allows better positioning of glenoid implants in total shoulder arthroplasty (TSA).[12,13,18] This has led to the development of many different preoperative planning software applications that allow 3D reconstruction of the shoulder and virtual positioning of the implants. The wide adoption of these software applications has contributed to improve the understanding of the 3D anatomy and deformity of the shoulder especially on the glenoid side.[9,10] However, this has also raised new questions regarding the ideal positioning of the implants. It seems clear that the objective after anatomic TSA is to restore the preoperative anatomy of the patient.[2] However, in cases of severe glenoid erosion and medialization of the joint line, it is also important to restore the patient's premorbid anatomy and therefore to find ways to determine this premorbid anatomy precisely.

Similarly in the setting of reverse TSA, optimal positioning of the implants and optimal lateral offset remain unclear. Nevertheless, it can be hypothesized that ideal tension of the remaining rotator cuff can be obtained by positioning the tuberosities at their anatomic premorbid position, and therefore, for these cases too, premorbid anatomy can be important to determine. Furthermore, glenoid bone loss may be encountered in other cases such as fracture or instability cases, and clinicians would benefit from knowing the precise shape of the premorbid glenoid and the premorbid position of the joint line.

One solution to determine a patient's premorbid glenoid anatomy could be to obtain a CT scan of the contralateral healthy shoulder and to use this shoulder as a surrogate for premorbid anatomy. However, several forensic and anthropologic studies have demonstrated that the traits of the posterior edge of the glenoid fossa could be used to determine hand dominance in early humans' skeletons,[7,20] suggesting that the human scapula is asymmetrical. The objective of this study was to compare the 3D anatomy of the glenoid between sides in a healthy population to determine whether the healthy contralateral shoulder can be used as a template for premorbid anatomy. We hypothesized that glenoid parameters would not differ significantly between sides.

Materials and methods

Study cohort

A multinational CT scan database was retrospectively reviewed for all healthy bilateral shoulders in patients aged between 18 and 50 years. CT scans were obtained from patients aged $\geq$18 years without shoulder pathology or injury in the setting of either polytrauma or traumatic head injury between January 2006 and October 2018. The patients' whole-body or upper-body CT scans were acquired with the following acquisition parameters: slice thickness $<$1.2 mm, number of slices $>$200, X-Y resolution $<$0.5 mm, matrix size of 512 $\times$ 512, 140 kV, and $>$300 mA. All CT scans were uploaded into a validated automated software program for 3D preoperative planning (Blueprint, version 4.0.1; Tornier, Montbonnot-Saint-Martin, France). Our final study sample included a total of 130 healthy bilateral shoulder CT scans, hence giving a total of 260 scapulae.

Measurements

Glenoid version, inclination, width, height, and lateral offset were computed using Blueprint 3D planning software.[3] The lateral offset between the 2 scapulae of a given subject was defined as the difference in the joint line position between the 2 glenoids and was measured using 2 different methods: glenoid lateral offset and scapula lateral offset.

The glenoid lateral offset was obtained by mirroring the left scapula for each case (Fig. 1). Then, the mirrored left scapula was automatically aligned with the right scapula without considering the glenoid articular surface (Fig. 2). The glenoid lateral offset was defined as the projection of the vector difference of the 2 glenoid centers on the transverse axis of the right scapula (Fig. 3).

The scapula lateral offset was also computed as it provided a measurement that did not rely on the first step of alignment of both scapulae. It was defined as the distance between the glenoid center and the most medial point of the trigonum scapulae projected on the transverse axis (Fig. 4).

Minimal detectable change

For each measure, the standard error of measurement (SEM) was computed, defined as

$$SEm = \sigma\sqrt{1\text{-}ICC}$$

where σ is the standard deviation of the whole scapula cohort (260 scapulae) and ICC is the intraclass correlation coefficient. From the SEM, we could deduce the minimal detectable change (MDC), which is the smallest difference between 2 single observations that can be confidently attributed to a genuine difference and not to measurement error. The MDC was defined as

$$MDC = 1.96\times\sqrt{2}\times SEm$$

Statistical analysis

For each measure, the average and the standard deviation of the paired differences were reported. To statistically quantify the

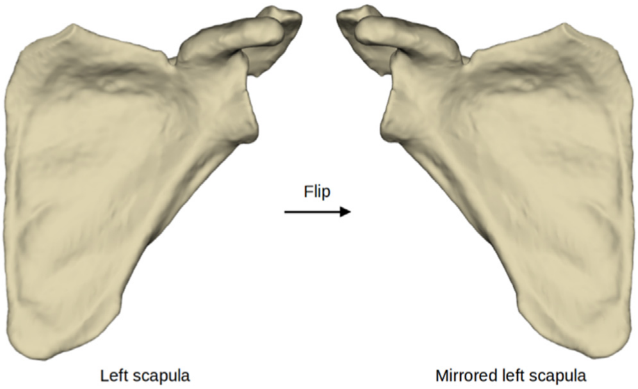

Figure 1 Left shoulder computed tomography scan reconstruction: mirroring left scapula.

correlation between left and right shoulders, the ICC was also reported, together with its 95% confidence interval. The ICC was interpreted using the guidelines described by Cicchetti[5] (Table I). Dependent samples were compared by use of the paired Student test. The level of statistical significance was set at $P < .05$.

Results

The comparison between 130 pairs of healthy scapulae showed statistically significant differences in mean version, inclination, and width, as well as scapula lateral offset (Table II). The glenoid lateral offset was not analyzed as this measure only makes sense for pairs of scapulae. The paired differences between left and right scapulae for all the measurement variables are reported in Table III. These mean differences were always inferior to the MDC regarding glenoid version, inclination, height, and width, as well as scapula offset (Table IV).

Very strong ICCs between the left and right shoulders were found for all evaluated paired measures (Table V). Again, the glenoid lateral offset was excluded as this measure only makes sense for pairs of scapulae.

Discussion

The main finding of this study was that there is a strong (version) or very strong (inclination, width, height, and scapula lateral offset) intraclass correlation between paired scapulae. Even though statistically significant differences existed between paired scapulae regarding version, inclination, width, and scapula offset, the mean differences observed between right and left scapulae were always inferior to the MDC.

Recently, Verhaegen et al[21] have reported equivalent mean paired differences for glenoid version and inclination between pairs of bilateral scapulae. Indeed, they found a mean paired difference of 2° for both measures in a smaller cohort of 66 patients. However, they did not conduct a statistical analysis and therefore were not able to find any statistically significant differences between the 2 scapulae of a given patient. In their study, they also analyzed differences in lateral offset between the 2 sides and found a mean difference of 2 mm by comparing the distance between the glenoid center and the trigonum scapulae. We chose to use 2 different measurement methods to assess differences in lateral offset without relying on the trigonum scapulae, which is known to be an imprecise landmark.[11]

The second measure we introduced to quantify glenoid erosion was the scapula lateral offset, which is the distance between the glenoid center and the most medial point of the trigonum projected on the transverse axis. The mean difference in the scapula lateral offset measured in our study between the paired scapulae is 1.3 ± 1 mm, which is also inferior to the difference of 2 mm reported by Verhaegen et al.[21] This scapula lateral offset measure has the advantage of being intrinsic to the scapula, which limits the risk of error. It appears to be highly invariant between the left and right shoulders, its ICC being equal to 0.98, which represents almost perfect agreement. However, this measurement can no longer be used when the scapula is truncated medially, which can occur if the CT scan is cropped. This is why we chose to describe and analyze both the glenoid lateral offset and the scapula lateral offset in our study.

We report differences that are, for the most part, statistically significant between paired scapulae. However, they remain very small at the scale of the scapula, and their clinical relevance can be questioned. Our results differ from what has been previously reported in several paleoanthropological studies[7,20] that have demonstrated that the scapulae of past human groups were more asymmetrical. One hypothesis could be that the activities of the modern subjects in our study may not be sufficient nor sufficiently unilateral in their stresses to cause an asymmetrical development of the upper limb. Clinically, the reported average differences are well below the precision offered by preoperative planning software coupled with patient-specific instrumentation. Indeed, in a recent study, Jacquot et al[14] evaluated the ability of a surgeon to reproduce intraoperatively freehand a preoperative 3D plan for anatomic TSA. They reported mean errors of 5° in glenoid implant version and 4° in inclination. More generally, most of the available published articles studying the accuracy of patient-specific instrumentation reported an accuracy within 5° in glenoid implant version and inclination.[4] These values are of the same magnitude as the computed MDCs for glenoid version and inclination found in our study. Therefore, the clinical relevance of the differences between healthy contralateral scapulae can be questioned, and our study shows, in agreement with the study of Verhaegen et al,[21] that the healthy contralateral scapula of patients with unilateral osteoarthritis can be used as a template for the premorbid anatomy of the pathologic scapula up to a precision that is equivalent to that given by patient-specific instrumentation.

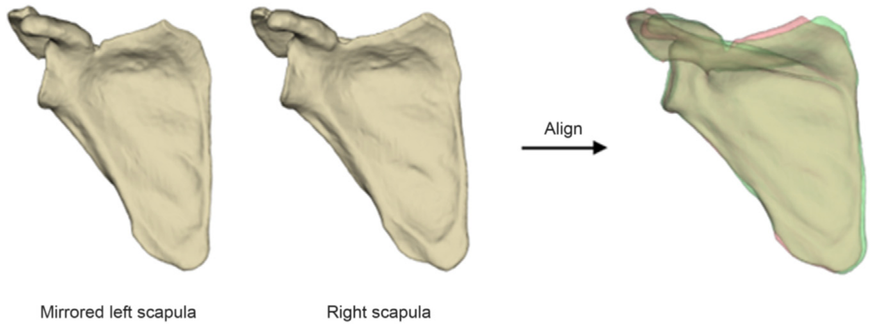

Figure 2 Shoulder computed tomography scan reconstruction: aligning mirrored left scapula with right scapula.

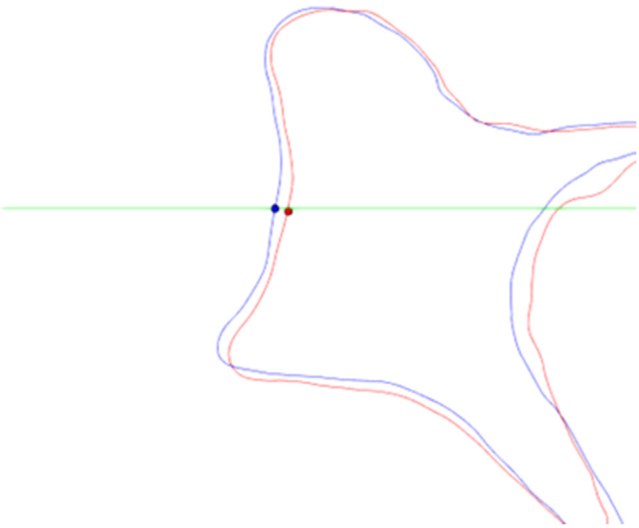

Figure 3 Shoulder computed tomography scan reconstruction. The lateral offset is defined as the lateral distance between the 2 glenoid centers (● and ●).

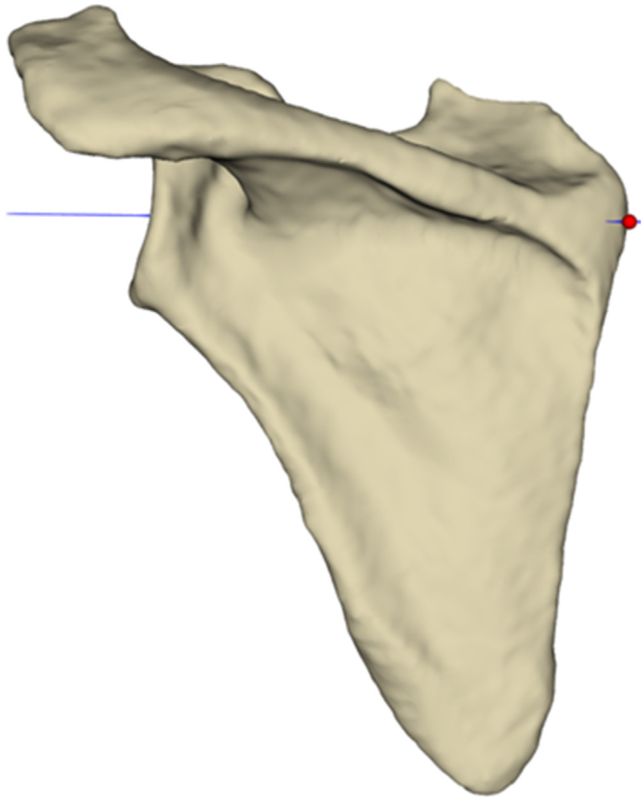

Figure 4 Shoulder computed tomography scan reconstruction. The ● is the most medial point of the trigonum scapulae projected on the transverse axis (–). The scapula lateral offset is defined as the distance between the glenoid center and this point.

Nevertheless, contralateral CT scans may not be easy to obtain routinely for preoperative planning. In addition, shoulder primary osteoarthritis often affects the contralateral side, which might also be exposed to degenerative changes, precluding its use to estimate premorbid anatomy. Thus, alternative methods to predict the premorbid anatomy of a pathologic shoulder could be useful. In 2008, Codsi et al[6] and Scalise et al[17,19] demonstrated that the endosteal surface of the glenoid defined as the ''glenoid vault'' is a highly consistent shape in healthy individuals. They showed that this glenoid vault can be reliably used to predict the premorbid anatomy of the glenoid by manually aligning and rescaling this vault model in a best-fit manner with the remaining portions of the eroded glenoid bone with an accuracy of $1.1° \pm 0.3°$ in normal healthy shoulders and an accuracy of $2.1° \pm 0.4°$ in arthritic shoulders. Abler et al[1] proposed a method to predict premorbid glenoid anatomy based on a local statistical shape model including the glenoid, as well as parts of the acromion and coracoid. They found that this technique could predict the overall surface of a healthy scapula with an accuracy of $2.3° \pm 1.8°$ for glenoid version, $2.1° \pm 2.0°$ for inclination, and 0.7 ± 0.5 mm for medialization of the joint line. In their study, they used the leave-one-out method to report the reconstruction error, which does not allow it to be proved that the premorbid shape can be reconstructed accurately for individual osteoarthritic glenoids. Likewise, Plessers et al[15] and Salhi et al[16] found similar accuracy in reconstructing artificial defects manually created using a statistical shape model of the entire scapula. Several different

Table I ICC intervals and their interpretation per guidelines of Cicchetti[5]

ICC	Interpretation
−0.2 to 0.2	Very weak
−0.4 to −0.2 and 0.2 to 0.4	Weak
−0.6 to −0.4 and 0.4 to 0.6	Moderate
−0.75 to −0.6 and 0.6 to 0.75	Strong
−1.0 to −0.75 and 0.75 to 1.0	Very strong

ICC, intraclass correlation coefficient.

Table II Measurement variables of left and right scapulae

Measurement	Left shoulder	Right shoulder	*P* value
Version, °	−4.6 ± 4.4	−5.3 ± 4.6	<.01*
Inclination, °	9.3 ± 5.2	8.4 ± 5.1	<.01*
Height, mm	33.3 ± 3.2	33.3 ± 3.1	.91
Width, mm	25.4 ± 2.5	25.6 ± 2.6	<.01*
Scapula offset, mm	106.2 ± 7.9	105.8 ± 7.7	<.01*

Data are presented as mean ± standard deviation, along with paired *t* test *P* value.
* Statistically significant.

Table III Paired absolute differences between left and right scapulae: means, standard deviations, and minimum and maximum values

Measurement	Difference	Minimum	Maximum
Version, °	2.2 ± 1.9	0	10
Inclination, °	2.2 ± 1.7	0	8
Height, mm	0.8 ± 0.6	0.0	2.4
Width, mm	0.8 ± 0.7	0.0	3.6
Scapula lateral offset, mm	1.3 ± 1.0	0.0	4.1
Glenoid lateral offset, mm	0.5 ± 0.4	0.0	1.6

prediction methods have been described and have been validated in a cohort of patients with unilateral osteoarthritis by making the assumption that the contralateral healthy shoulder could be used as a template for premorbid anatomy.[8,19] However, to our knowledge, no previous study has confirmed that the contralateral scapula could be used to predict premorbid anatomy.

The use of the healthy contralateral scapula as a premorbid template is confirmed by the results of our study if the claimed accuracy is of the same magnitude as patient-specific instrumentation. However, we are engaged in building a more robust validation protocol for future prediction methods in which we will be able to determine whether the ICCs for glenoid measurements between the premorbid prediction and the healthy contralateral scapula are equivalent to the ones reported in this study—and that the average paired differences are inferior to the MDCs also reported in this study.

Table IV SEM and MDC between left and right scapulae

Measurement	SEM	MDC
Version, °	2.1	5.8
Inclination, °	2.0	5.4
Height, mm	0.7	2.0
Width, mm	0.7	2.0
Scapula offset, mm	1.1	3.2

SEM, standard error of measurement; *MDC*, minimal detectable change.

Table V ICC and 95% CI between left and right scapulae

Measurement	ICC	95% CI
Version	0.79	0.71-0.84
Inclination	0.86	0.81-0.90
Height	0.95	0.93-0.96
Width	0.93	0.88-0.94
Scapula offset	0.98	0.97-0.99

ICC, intraclass correlation coefficient; *CI*, confidence interval.

Our study has several limitations. First, the study is limited by the weaknesses of its retrospective nature. Moreover, the hand dominance of the patients is unknown, and it would have been interesting to determine whether hand dominance affected the measures performed in our study. Second, all CT scans were obtained from patients with no history of shoulder problems; however, we cannot exclude that there have been small unnoticed changes in the osseous morphology of the included scapulae. Finally, we did not provide a definitive measure of the difference in depth between the 2 glenoids. Both glenoid lateral offset and scapula lateral offset have their strengths and weaknesses and should be used depending on the context. The strength of our study is that it is the first study, to our knowledge, to compare healthy scapulae in a large cohort of healthy patients.

Conclusion

Healthy contralateral scapulae are highly reliable to predict inclination, height, width, and scapula offset and are reliable to predict version of a given scapula. Paired right and left scapulae were not statistically symmetrical regarding mean glenoid version, inclination, and width, as well as scapula offset. Nevertheless, the reported differences were not higher than the MDC for this cohort, confirming that healthy contralateral shoulders can be a useful template in TSA preoperative planning.

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