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ORIGINAL ARTICLE • SHOULDER - ARTHROPLASTY

A new geometric model to quantify the area of glenoid bone defect and medialisation of the native joint line in glenohumeral arthritis

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Abstract

Purpose To propose a geometric model to quantify the bone defect and the glenoid medialisation (in millimetres) compared to the native joint line. We also evaluated the reliability of this geometric model.

Methods Using two-dimensional CT imaging, we built a hypothetical triangle on the axial scan consisting of the following: side A, length (millimetres) of the glenoid bone; side B, average length (millimetres) of the glenoid in a healthy population; side C, the missing side; and angle α, the retroversion angle calculated using the Friedman method. The resulting triangle represents the bone defect, and its height represents the medialisation of the native joint line. To estimate inter-operator reliability, two physicians (operator 1 and operator 2) took the following measurements: angle α, side A, side C, semi-perimeter, area defect and height.

Results Forty participants (mean age ± SD 45 ± 10 years, range 26–43 years)—22 women and 18 men—participated in the study. We applied the cosine theorem (Carnot theorem) to calculate side C. After obtaining the three sides, the area of the triangle can be determined. Once the area is known, it is possible to extrapolate the height of the triangle, which corresponds to the loss of vault depth due to the bone defect. With respect to inter-operator reliability, the ICCs for all measurements were > 0.99, exhibiting a very high correlation.

Conclusions The proposed geometric model can be used to quantify the glenoid bone deficit and the glenoid medialisation compared to the native joint line, which can be used to improve surgical treatment.

Keywords Shoulder · Reverse arthroplasty · Glenoid · Bone graft · Bone loss

Introduction

Reverse shoulder arthroplasty (RSA) implants are increasing worldwide [1–3]. The growing popularity can be attributed to the patient's functional recovery, which is preserved over time independent of the rotator cuff. In addition, newer prosthetic designs enable lateralisation of the humerus, conferring improved stability and biomechanics of joint matching. RSA has become a valid treatment option for patients with primary osteoarthritis with rotator cuff tear, and even those with partial or significant glenoid bone loss [4].

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To date, glenoid implants represent the most critical step in total shoulder arthroplasty, as most causes of failure are due to wear and loosening on the glenoid side [5, 6].

Glenoid bone defects are among the most challenging preoperative problems associated with RSA. As a result, some authors consider large defects to be a contraindication for glenoid implants [7]. The ability to objectively quantify the glenoid bone deficit would allow better surgical planning, thereby reducing the number of implants with unsatisfactory outcomes [8, 9]. However, measuring the glenoid defect is complicated because of its tridimensional shape. A healthy glenoid vault has a conic shape with a medial apex and lateral base, corresponding to the glenoid fossa [10–12].

The identification and quantification of bone loss in a three-dimensional geometry is unsuitable from a surgical point of view. According to the geometrical considerations of Codsi [13], it is easier to consider the cross-sectional area of the vault along the vertical axis due to the triangular shape. This simplified model reduces the endosteal

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geometrical complexity of the glenoid vault satisfying the glenoid form for 99% and keeping the volume of vault unchanged respect the original shape. Using the triangle method for the glenoid vault, it is possible to identify a healthy or pathological triangle during CT evaluation in an axial view. Regarding arthritic glenoids, most cases involve a posterior defect with bone loss. This new triangle represents the bone defect, the height of which represents the medialisation of the native joint line.

The ability to quantify the missing bone simplifies preoperative planning to reconstruct the glenoid anatomy and restore the native joint line.

The first aim of this study was to propose a geometric model to quantify the bone defect and the glenoid medialisation (in millimetres) compared to the native joint line.

To be clinically useful on a daily basis, a measurement system needs to be accurate, easy to use, and able to generate reliable results. Thus, we also evaluated the reliability of this geometric model.

Materials and methods

All procedures performed in studies were in accordance with the ethical standards of the institutional and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Informed consent was obtained from all individual participants included in the study.

All CT scans of patients with a primary diagnosis of rotator cuff tear arthropathy and treated by the senior authors for reverse shoulder arthroplasty (RSA) between January 2018 and December 2018 were enrolled in this study.

Patients who had previous shoulder surgery were excluded.

All CT scans were acquired with a GE Lightspeed QZ/i (GE Healthcare, Waukesha, WI) helical scanner in the supine position. CT images were acquired in an axial view with the following scanning parameters: 1.25 mm contiguous slices, pixel size ~ 0.395 mm, ~ 20 cm field of view, 512 × 512 matrix through the shoulder joint. The images were stored in Digital Imaging and Communication in Medicine (DICOM) format and then transferred to computers for analysis.

All CT scans were acquired with use of Philips Computerized Tomography (MX 8000 16 layers; GE Light Speed 16 layers) in the supine position. CT images were acquired in an axial view with the following scanning parameters: pixels are square and constant for all the image, the resolution for an image was 0.3 × 0.3 mm/pixel (i.e. 512 pixels represent at least 154 mm), and the inter-space distance between consecutive slices is constant for the whole exam.

The images were stored in Digital Imaging and Communication in Medicine (DICOM) format and then transferred to computers for analysis.

The CT scan images are pure axial slices (gantry tilt = 0°).

The examination includes the entire scapula, complete to medial border and distal tip.

Procedure

Presentation of geometric model: in two-dimensional CT imaging, according to Codsi geometrical considerations [13], the majority of glenoid bone loss is associated with the retroversion angle. The hypothetical triangle used to perform measurements is the triangle obtained in the axial scan. This triangle can be used to calculate the glenoid version angle according to the model described by Friedman [14], who stated 'The coracoid process was identified, and measurements of glenoid version were made on the next four slices inferior to the coracoid process, corresponding approximately to the mid-glenoid level'.

The cosine theorem (Carnot theorem) is applied at the base of the geometric model. In trigonometry, the cosine theorem expresses a relationship between the length of the sides of a triangle and the cosine of one of its angles. Therefore, by knowing the length of two sides and the angle between them, the length of the third side can be obtained for any triangle.

Based on our geometric model, we obtained a hypothetical triangle (Fig. 1) represented by: side A, length (millimetres) of the glenoid bone; side B, average length (millimetres) of the glenoid in a healthy population [15]; side C, missing side; and angle α, the retroversion angle calculated using the Friedman method.

To estimate inter-operator reliability, two physicians (operator 1 and operator 2) took the following measurements: angle α, side A, side C, semi-perimeter, area defect and height.

Both operators made their evaluations independently and were blinded to each other's procedures and results.

Sample size

With respect to measurement of reliability, power calculation was based on the intra-class correlation coefficient (ICC). On assumption of a two-tailed α value of 0.05 (sensitivity = 95%), a β value of 0.20 (study power = 80%), we determined that at least 40 participants were required (Power Analysis and Sample Size System software) (G*Power 3, Heinrich Heine University, Düsseldorf, Germany).

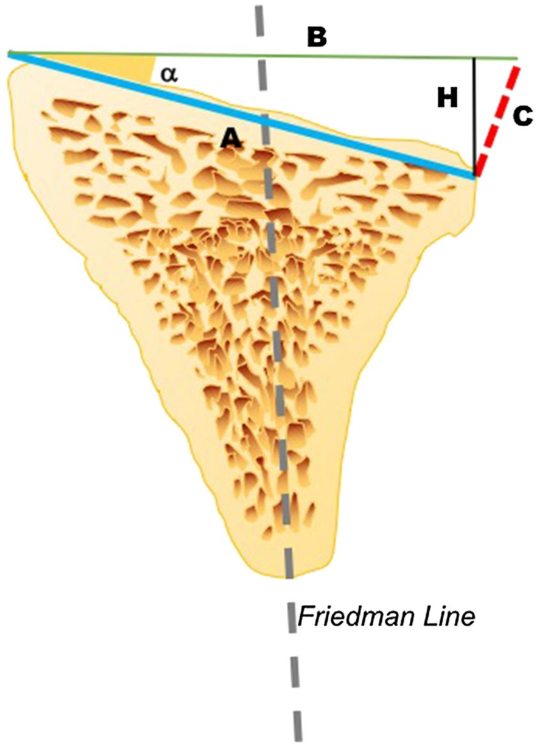

Fig. 1 Hypothetical triangle represented by side a: length in mm of the glenoid bone; side b: average length in mm of the glenoid in the healthy population; side c: missing side; angle α: retroversion angle calculated in according to the Friedman method; and H: height of the defect that represents glenoid medialisation compared to the native joint line

Statistical analysis

All data were analysed by a single-blinded researcher with use of SPSS software (version 18; SPSS, Chicago, Illinois). Calculated p values were two-sided, with $p < 0.05$ considered significant, and all results are reported with a 95% confidence interval (CI). A Kolmogorov–Smirnov test was used to verify the normal distribution of the data.

The ICC, with a 95% CI, was calculated to assess reliability. In particular, the ICC [16–18] was used to determine inter-rater reproducibility. The ICC, which is the most suitable statistical test for the assessment of reliability, can range from 0 to 1: 0.00–0.25 indicates little or no correlation, 0.26–0.49 indicates low correlation, 0.50–0.69 indicates moderate correlation, 0.70–0.89 indicates high correlation, 0.90–0.99 indicates very high correlation, and 1 indicates perfect correlation.

Results

Forty participants (mean age ± SD 45 ± 10 years, range 26–43 years)—22 women and 18 men—participated in the study.

In our model, we know the length of sides A and B and angle α. Using the cosine theorem, it is possible to determine the length of side C, representing the bone deficit, according to the following equation:

$$C^2 = A^2 + B^2 - 2AB\cos\alpha$$

After obtaining the length of the three sides, the area of the triangle can be calculated according to the following equation:

$$A = \sqrt{p} \cdot (p-a) \cdot (p-b) \cdot (p-c)$$

where p is the semi-perimeter, calculated as:

$$p = \frac{a+b+c}{2}$$

Side B, the average length of the glenoid in a healthy population, is a range, and thus, it includes a minimum and maximum value. Therefore, side C and the calculated area will also have a minimum and maximum range (Fig. 2).

Knowing the area and base of the triangle (represented by side A), it is possible to extrapolate the height (h) of the triangle, corresponding to the loss of vault depth due to the bone defect:

$$\text{Area} = \text{base} \times h/2 -> h = \text{Area} \times 2/\text{base} -> h = \text{Area} \times 2/\text{side A}$$

The height of the defect is an important landmark because it represents the real glenoid medialisation (in millimetres) compared to the native joint line.

Reliability

Inter-operator and intra-operator test–retest reliability values are reported in Table 1. With respect to inter-operator reliability, the ICCs for all measurements were > 0.99, exhibiting a very high correlation.

Discussion

The main objective of this study was to quantify the area of the glenoid vault bone defect, necessary to reconstruct the glenoid anatomy, as well as to quantify the glenoid medialisation (in millimetres) compared to the native joint line.

To be clinically useful on a daily basis, a measurement system needs to be accurate, easy to use, and able to generate reliable results. Indeed, we conducted a reliability evaluation of this geometric model to allow its use in clinical practice. According to inter-operator reliability, we found very high ICC values for all variables considered.

The height of the triangle obtained using the proposed geometric model represents the extent to which the joint

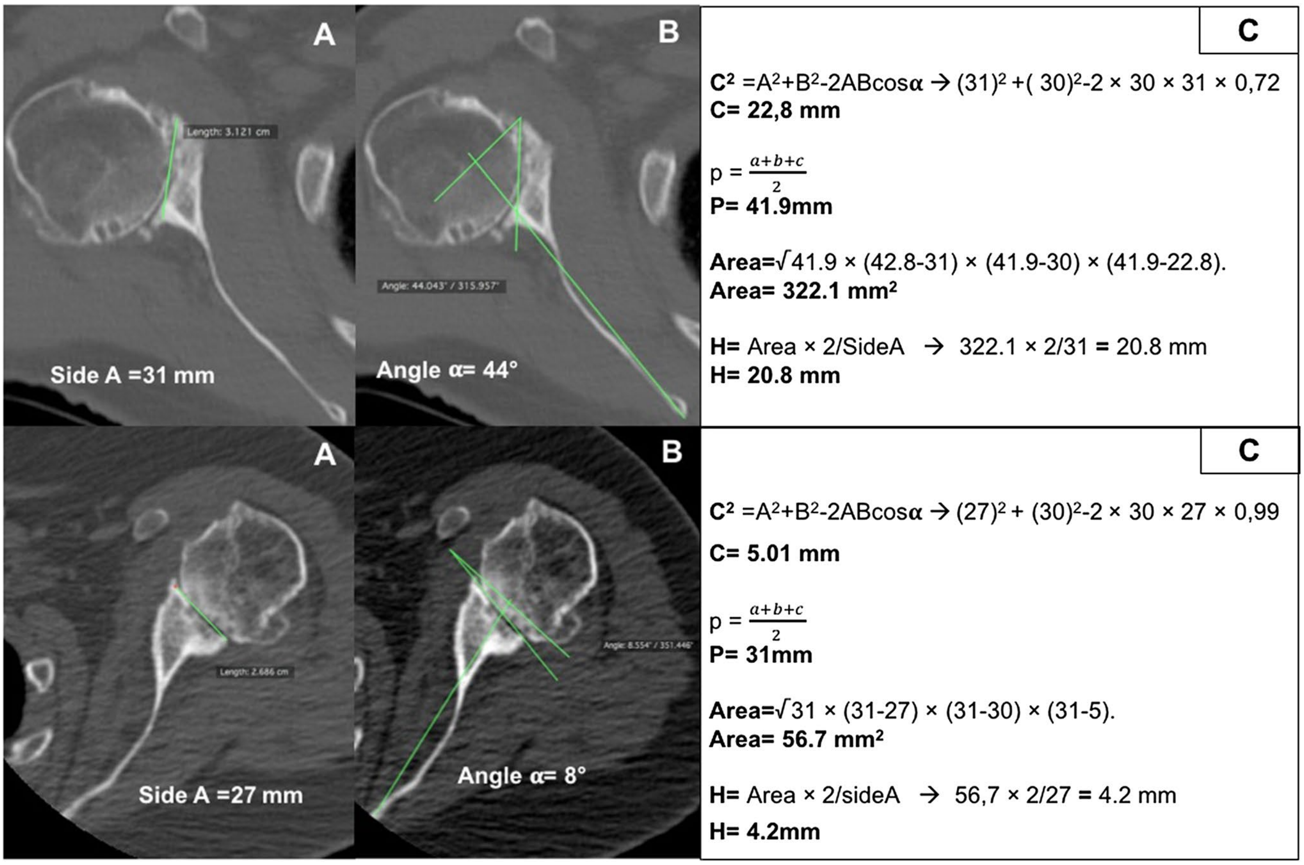

Fig. 2 A practical example of the proposed theorem. **a** Evaluation of length in mm of the glenoid bone; **b** evaluation of retroversion angle calculated according to the Friedman method; **c** using the cosine theorem, it is possible to determine the length of side C, and according to the equations, it is possible to evaluate the area of hypothetical triangle and the height of triangle which represents the medialisation in millimetres of the native joint line

Table 1 Inter-operator and intra-operator test–retest reliability values exhibiting a very high correlation

	ICC*	CI 95%	
		Low	High
Inter-operator			
Angle A	0.996	0.980	1.00
Side A	0.979	0.956	0.995
Side C	0.998	0.997	1.00
Semi-perimeter	0.983	0.964	0.996
Area defect	0.991	0.981	0.997
Height	0.993	0.986	0.996

ICC intra-class correlation coefficient, *CI* confidence interval

[a]Average values

line has receded. This is valuable information to know preoperatively and can be used to better guide the surgeon in decision-making regarding the operative strategy for glenoid surgery. As a result, the surgeon may, for example, consider the possibility of eccentric reaming of the augmented prosthetic component, a graft or a combined technique.

The correct positioning and fixation of the glenoid is one of the most challenging aspects of the procedure, which influence both short- and long-term results [5, 6].

Proper glenoid preparation may be the most critical step in total shoulder arthroplasty, as most causes of failure can be attributed to wear and loosening on the glenoid side. Careful preoperative planning is required to better understand the bony anatomy so that the surgical plan can be adjusted accordingly [8]. The goals of glenoid preparation are to correct any abnormalities in version, leaving behind enough bone in the vault to support the implant, and restore the joint line to provide a stable and high-performance implant. In RSA, the glenoid bone–metal interface is the surface subjected to the greatest stress [9, 19]. If the residual vault is too small in depth, an implant could break through the medial cortex of the vault or have insufficient bone support to be stable.

There are three main surgical options: asymmetric reaming, bone grafting, and augmented implants. In cases of posterior erosion less than 1 cm and retroversion less than 15°, many authors suggest anterior glenoid eccentric reaming to offset the deformity. Corrections greater than 15° should be avoided as they may violate the glenoid vault, resulting in implant penetration upon insertion [20, 21]. When the deficiency exceeds 1 cm and the glenoid is retroverted more than 25°, bone grafting with internal fixation should be used, although this technique has had mixed results [22, 23].

Our work adds a new and important parameter to the preoperative planning process, allowing the determination of how far the joint line has moved back (measured in millimetres). The ability to quantify the glenoid defect in its medial extension and, consequently, the loss of depth of the glenoid vault allow the surgeon to preoperatively evaluate the tightness of the potential metaglenoid implant. The main problem comes from the bone structure in which the metal is placed, which, after sufficient reaming, is already at the minimum surface depth and diameter. Furthermore, the biomechanical design of the inverse prostheses ensures that the bone–glenoid component interface takes the greatest amount of functional load and stress caused by the moment of rotation, muscle tension, joint reaction force, and deltoid wrapping [9, 19].

Poor evaluations that compare healthy shoulders to shoulders with osteoarthritis show that there can be a reduction in depth of the vault in the equatorial region of the glenoid by a third or less of the average depth of the healthy vault, which is 24 + 3 mm. This implies that shoulders with osteoarthritis have insufficient bone stock for the implantation of an inverse metal back. For these reasons, it is important to correctly quantify the missing bone area in order to restore version and the native glenoid joint line.

The current classification systems provide a good description of the bone loss, but do not provide the surgeon with an intra-operative tool to address the bone loss, and do not provide any guidelines to achieve a successful single-stage procedure in patients with significant bone loss. In addition, the actual bone loss is not quantified in square millimetres and does not provide any indication of the quantity of glenoid vault that will remain.

All classifications are predominantly morphological [14, 23–25], providing ways in which to qualitatively evaluate the defect in terms of retroversion with more or less accentuated angles, as well as the location of the bone defect, but they do not define the tissue loss in millimetres. Quantification of the bone loss is very important as it provides more precise measures to assist in preoperative planning. Moreover, many companies provide software that allow preoperative three-dimensional glena evaluation. However, these programmes have some limitations, as they are expensive, they are not always available, they are designed for individual implant systems, and thus, the choice of prosthetic implants is limited, and they cannot quantify the real defect in millimetres. Our method provides each surgeon with a simple and reproducible system which is able to preoperatively indicate the real dimensions of bone loss through CT evaluation, allowing it to be addressed with a suitable surgical solution including eccentric reaming, grafting, or an augmented prosthesis component.

Other studies are necessary to validate the proposed method intra-operatively.

The proposed model presents some limitations. The main limitation is that the healthy glenoid is taken as a measurement, which does not necessarily correspond to the original value of the patient's glenoid. However, as the length of the glena is relatively constant, only varying by few millimetres between patients, this should have a minor effect on the area of the bone defect, measured in square millimetres.

The proposed geometric model quantifies the glenoid bone deficit and glenoid medialisation compared to the native joint line, which can be used to improve surgical treatment.

Compliance with ethical standards

Conflict of interest Riccardo Maria Lanzetti and Marco Spoliti have no conflict of interest.

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