ORIGINAL ARTICLE

Three-dimensional measurement method of arthritic glenoid cavity morphology: Feasibility and reproducibility

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Summary

Introduction: Glenoid component loosening is the main complication of total shoulder arthroplasty. Better knowledge of the arthritic glenoid cavity anatomy can help in developing new implants and techniques. The goal of this study was to describe and validate the reproducibility of a CT scan-based, 3D measurement method used to describe various parameters characterizing arthritic glenoid cavity morphology.

Materials and methods: Twelve CT scans and 29 CT arthrogram were evaluated. These scans were taken from 41 patients with glenohumeral osteoarthritis who received an anatomical shoulder prosthesis. A 3D reconstruction of the scapula was performed based on the DICOM files. Following the 3D volume acquisition, points on the glenoid articular surface were manually extracted by three observers, each one three times, allowing one week between readings, to determine the inter- and intra-observer reproducibility. The intraclass correlation coefficient (ICC) was calculated on five 3D parameters that were automatically calculated: glenoïd height, glenoid width, height at maximum width glenoid version and radius of the articular surface best-fit sphere.

Results: The intra-observer and inter-observer ICC were 0.91 to 0.99, and 0.95 to 0.99, respectively.

Discussion: This study is the first to report on a reproducible 3D measurement method, based on CT scans, for the arthritic glenoid cavity, which derives the joint radius of curvature among other morphology parameters. These 3D measurements are advantageous because they are free of problems related to patient positioning in the CT scanner and to the choice of slices,

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which limits the accuracy of measurements made on slices from 2D CT scans. Three-dimensional methodology similar to ours has been validated on healthy glenoids.

Conclusion: This study confirms the reliability and good reproducibility of our method, which allows us to extend this method to a larger patient cohort and adapt this automated technology to preoperative planning software.

Level of evidence: Level 4 study.

Introduction

Because of the significant loosening rate, survival of the glenoid implant component over time is the main challenge with anatomical total shoulder arthroplasty (TSA) [1]. Many factors affect glenoid loosening such as implant position (version and inclination), cementing technique, type of implant and more recently, the amount of reaming [1]. In 1972, Neer used a single glenoid component size, which was completely made of polyethylene, during the first TSA cases [2]. Currently, most of the implants have three to five sizes that gradually increase in height (superior-inferior) and width (anterior-posterior) but have a single radius of curvature at the bone/interface implant. The choice of size and radius of curvature for these implants is based on the results of anatomical studies performed on healthy (non-arthritic) glenoid articular surfaces [3,4].

Information about various 3D parameters of arthritic glenoid anatomy, especially the radius of curvature of the articular surface, would seem to be important information to improve the design of the glenoid implant component. To our knowledge, this parameter has never been evaluated in 3D on arthritic glenoids, in contrast to version [5—7] and the bone architecture of the glenoid vault [8,9].

The goal of this study was to describe and validate the reproducibility of a CT scan-based, 3D measurement method used to describe various parameters of arthritic glenoid morphology, including size, version and radius of curvature.

Material and methods

Starting with a database of 145 CT scans or CT arthrography scans digitized onto CD that belonged to patients receiving anatomical TSA for primary glenohumeral osteoarthritis, 12 CT scans and 29 CT arthrography scans were analysed for this study. These 41 files were chosen from the database by drawing lots. In 26 cases, the arthritic glenoid had a Type A wear pattern, and in 15 cases, it had a Type B pattern [10].

3D reconstruction of the scapula

Two different protocols were used with the CT scan and CT arthrography scan digitized DICOM data to perform a 3D reconstruction of the scapula. For all the CT scans, 3D reconstruction of the scapula was performed using an automated segmentation process in the Glenosys 1.0 software (Imascap; Brest; France). The morphological structure of the proximal humerus, scapula and glenoid is analysed and automatically recognized by the software. For all the CT arthrography scans, a three-step, semi-automated segmentation process was used: automatic thresholding based on

pixel intensity; manual extraction of intra-articular contrast product (same density as the bone cortex) and automated 3D reconstruction with image smoothing.

With these 3D reconstructed scapulas, three experienced orthopaedic surgeons used the Glenosys software to manually extract the contour of the glenoid articular surface (Fig. 1). Based on these extracted points, the glenoid articular surface was defined for each scapula. Then the superior point (SUP = highest point on the glenoid articular surface) and the inferior point (INF = lowest point on the glenoid articular surface) were chosen manually with the same software (Fig. 1).

Measurement of various parameters to describe arthritic glenoid morphology

After the glenoid articular surface and superior and inferior points on the 3D scapula were acquired, the Glenosys software calculated the following five morphology parameters: height (H) and width (L) of the glenoid articular surface; height at the maximum width (H_L); glenoid version (V) and glenoid articular surface best-fit sphere.

Height, width and height at max width were calculated in the glenoid coordinate system and the best-fit sphere was calculated in the scapula coordinate system. Each
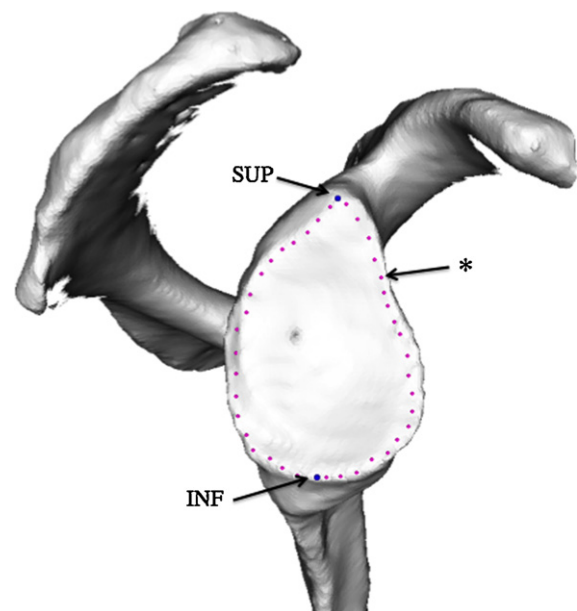

Figure 1 Manual extraction of the contour of the glenoid articular surface by selecting points (*) at the top of the edge of the glenoid rim with the Glenosys 1.0 software. The superior (SUP) and inferior (INF) points are then selected manually.
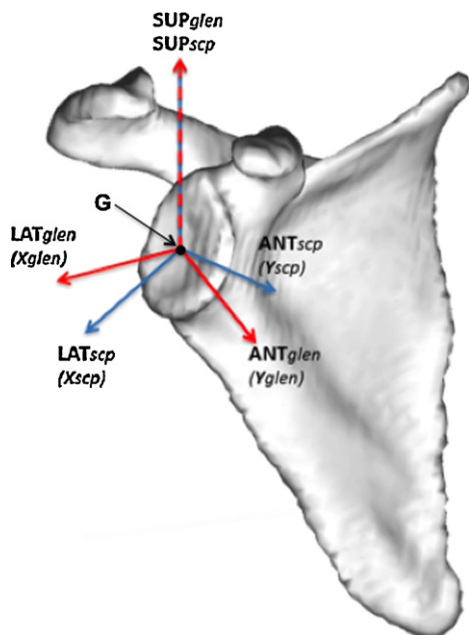
Figure 2 The centre of the two coordinate systems corresponds to the centre of gravity of the glenoid surface (G). The glenoid coordinate system is defined by three vectors (SUPglen, ANTglen and LATglen). The scapula coordinate system is defined by three vectors (SUPscap, ANTscap and LATscap).

coordinate system was defined by a centre and three orthogonal vectors (Fig. 2). The centre (centre of gravity of the glenoid articular surface) was automatically calculated and was the same for both coordinate systems (G). The three vectors of the scapula coordinate system were the SUP Scap (vertical axis formed by the intersection of the scapula plane and the glenoid plane, oriented from lower to upper), ANT Scap (sagittal axis oriented back to front and perpendicular to the scapula plane) and LAT Scap (frontal axis oriental medial to lateral and perpendicular to the other two vectors). The three vectors of the glenoid coordinate system were the SUP Glen (vertical axis formed by the intersection of the scapula plane and the glenoid plane, oriented from lower to upper), LAT Glen (frontal axis oriented medial to lateral and perpendicular to the glenoid plane) and ANT Glen (sagittal axis oriented back to front and perpendicular to the other two vectors):

- the height of the glenoid articular surface was calculated as the 3D Euclidean distance between the superior and inferior point of the articular surface (Fig. 3);
- the width of the glenoid articular surface was calculated as the 3D Euclidean distance between the anterior (ANT_L) and posterior ($POST_L$) points on the articular surface. These two points (anterior and posterior) were automatically calculated and defined as belonging to the contour of the glenoid articular surface and to the plane (L-plane) perpendicular to the SUP/INF axis where the 3D Euclidean distance ($d(ANT_L-POST_L)$) is the greatest (Fig. 3);
- the height at maximum width was calculated as the 3D Euclidean distance along the INF/SUP axis, between the inferior point and the intersection of the two lines (ANT_L-POST_L) and ($SUP-INF$) (Fig. 3).
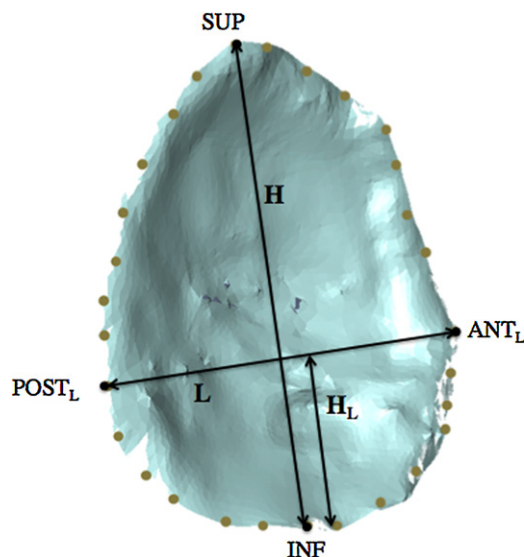

Figure 3 Measurements made on the glenoid articular surface: height (H); width (L); height at Max Width (H_L); anterior (ANT_L) and posterior ($POST_L$) points; superior (SUP) and inferior (INF) points.

- version was calculated between the scapula and glenoid planes, and also corresponds to the angle between the anterior vector in the scapula coordinate system (ANT Scap) and the anterior vector in the glenoid coordinate system (ANT Glen). The scapula plane was defined as the average plane calculated from the least-square method applied to all the scapula points, by weighing them differently. This plane was automatically calculated by the Glenosys software. The glenoid plane was calculated with the least squares method applied to all the points on the manually extracted glenoid articular surface (Fig. 4);
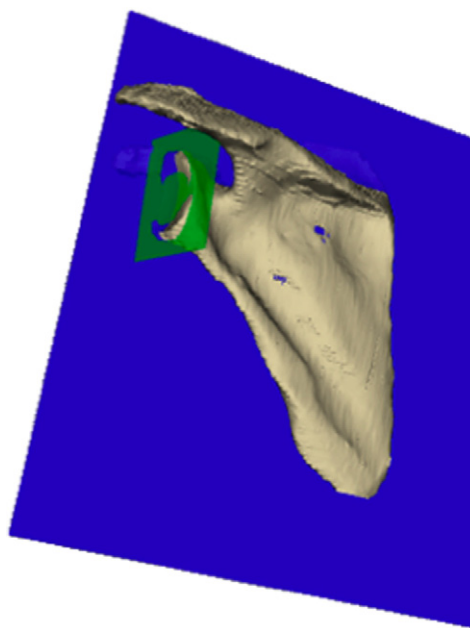
Figure 4 Glenoid and scapula planes on a 3D reconstructed scapula.
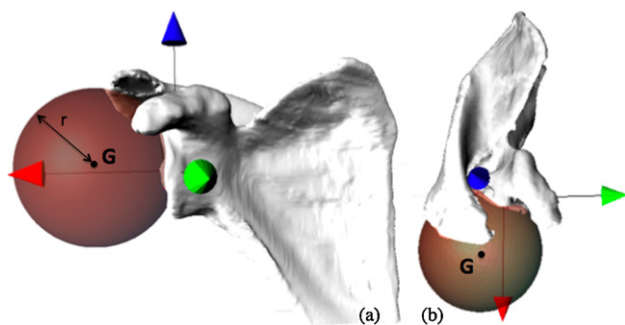
Figure 5 The best-fit sphere on the articular surface of an arthritic glenoid with a frontal (a) and superior (b) view. Centre of gravity (G) and radius of curvature (r) of the best-fit sphere.

- the best-fit sphere for the glenoid articular surface was used to calculate the average radius of curvature for the articular surface. This best-fit sphere was defined by the radius of this sphere and its centre of rotation, with the coordinates given in the scapula coordinate system. The coordinates of the centre (G) and the radius of the sphere (r) were determined using the classic mathematical approach of minimizing the sum of squared errors in the distance between the points on the sphere and the points on the glenoid articular surface (Fig. 5).

Reproducibility study

The reproducibility of measuring the five previously described parameters [11,12] was evaluated here.

Intra-observer reproducibility: the same observer manually extracted the glenoid articular surface and the superior and inferior points on the 41 reconstructed scapulas three times with one week between each trial. The intraclass correlation coefficient (ICC) was determined for the five calculated parameters (H, L, HL, v, radius of best-fit sphere) along with 95% confidence intervals.

Inter-observer reproducibility: three observers manually extracted the glenoid articular surface and the superior and inferior points on the 41 reconstructed scapulas twice, with one week between each trial. Two intraclass correlation coefficients were determined for the five calculated parameters (H, L, HL, v, radius of best-fit sphere) along with 95% confidence intervals. One ICC was determined for the first series of measurements for each observer and a second ICC was determined for the second series of measurements.

Results

The measurement results from all three observers are summarized in Table 1.

For the intra-observer reproducibility, the correlation coefficient ranged from 0.91 to 0.99 for the five measurements (Table 2). For the interobserver reproducibility, the correlation coefficient ranged from 0.95 to 0.99 (Table 3).

Discussion

Because CT scans are better than conventional X-rays [13], glenoid anatomy [10,14] and version [15] are typically evaluated on 2D slices from the raw CT scan images during preoperative planning for total shoulder arthroplasty. More recently, 3D measurements from CT scan reconstructions were developed to evaluate glenoid version [5–9,16–21]. Most of these studies were performed on healthy glenoids, cadaver specimens or patients with a proximal humerus fracture [15–21], then adapted to pathological glenoids [5–9].

Our results confirm the hypothesis that our 3D measurement method of arthritic glenoid morphology based on CT scan 3D reconstructions is feasible and has very good inter- and intra-observer reproducibility (correlation coefficient always greater than 0.91).

The reproducibility of CT scan 2D measurements for glenoid version had previously been demonstrated [9,15,16], with measurement variability around 1.5° and correlation coefficients between 0.95 and 0.98 [9,16,21]. However according to Friedman et al. [15], the errors associated with this type of measurement are mainly due to patient positioning during acquisition of the CT scan images [6,22,23]. Bokor et al. [22] showed that a 15° variation in scapula orientation relative to the reference position during image acquisition leads to errors of more than 10° in version measurement. Hoenecke et al. [6] compared the measurement of glenoid version on raw CT scan images to the version measured on slices from 3D reconstruction. In 20% of cases, the error was more than 10°; an average of 7° variation in the version measurement occurs if the selected slice is just below the end of the coracoid process. This variability can be attributed to the glenoid having a different version, depending on the height of the chosen slice [19]. Hoenecke et al. reported that the version measurement error was 1° or less in 91% of cases with their method. They concluded that use of 3D reconstruction was preferable when choosing which 2D slice to use to reliably measure the glenoid version [6]. Budge

Table 1 Results for the five measured parameters.

	Average (± SD)	Minimum	Maximum
Height (mm)	41.33 (± 5.5)	31.5	55.1
Width (mm)	29.35 (± 5.2)	19.6	44.8
Height at Max Width (mm)	19.95 (± 3.1)	15.1	28.4
Version (°)	−12.1° (± 10.8)	23.1	−28.7
Radius of best-fit sphere (mm)	34.9 (± 9.2)	21.7	65.5

SD: standard deviation.

Table 2 Intra-observer reproducibility.

	ICC	95% confidence interval
Height	0.94	0.89 to 0.96
Width	0.99	0.98 to 0.99
Height at Max Width	0.91	0.86 to 0.95
Version	0.997	0.996 to 0.998
Radius of best-fit sphere	0.96	0.94 to 0.98

et al. validated a measurement method that was similar to the one used by Hoenecke [21]. These methods [6,21] correspond to a first attempt to calculate a fully 3D glenoid version, based on CT scan reconstruction [5,8,9,16,17]. The accuracy of using CT scan 3D reconstruction by segmenting raw CT scan images relative to taking real measurements on cadaver scapula specimens was demonstrated by both Kwon [16] and Bryce [23].

Three-dimensional measurement methods for glenoid version consist of calculating the angle between the scapula plane and the glenoid plane. These methods require manual acquisition of at least three points on the scapula to define the scapula plane and at least three point on the glenoid articular surface to define the average glenoid plane [17]. At least three points are needed to define a plane. The glenoid plane can be defined in the most reproducible manner with three points: anterior, posterior and inferior [24]. But this method does not take the entire superior part of the glenoid into account. We chose to use to use all the glenoid-defining points to obtain the best reproducibility when calculating the average glenoid plane, which makes it independent of manually acquiring only three points. This also applies to the scapula plane, which is defined by three points in the published literature [16,17,19,24]. The reproducibility of these 3D measurements, validated on non-arthritic glenoids, is good (correlation coefficient between 0.90 and 0.99) [9,17,19].

The measurement of radius of curvature of the glenoid articular surface has been described little in the published literature [19,20,25,26]. The radius of curvature has only been evaluated in non-arthritic glenoids based on X-ray [25,26], 2D CT scan [25], 3D CT scan reconstructions [19,20] and even MRI [27] studies. Lewis et al. [19] use a similar approach to ours to calculate the best-fit sphere for the manually extracted glenoid articular surface, using CT scan 3D reconstructions. They also described an original method to calculate 3D version and inclination from the

best-fit sphere with good inter- and intra-observer reproducibility (correlation coefficient greater than 0.90). As with the glenoid version measurement, it is preferable to evaluate the glenoid radius of curvature by evaluating the average curvature of the entire glenoid surface with a best-fit sphere instead of calculating the curvature of the glenoid surface with only one slice. Similarly to version, the radius of curvature of the glenoid cavity varies as a function of glenoid height [23].

But our radius of curvature results are difficult to compare with other studies because, many authors validated their methods on healthy patients, cadaver specimens or non-arthritic glenoids [19,20]; the measurement method was different (X-ray and CT scan) [25,26]. The average glenoid version measured with 3D methods was between −8.6° and −19° [6,7,9]. Our average version was in this range. These differences can be explained by patient selection based on glenoid wear according to the Walch classification on one hand, and by the different measurement methods used, on the other hand.

Our method to measure arthritic glenoid morphology parameters (version, radius of curvature, height and width) from CT scan 3D reconstructions has many advantages:

- all the measurements are calculated in 3D coordinate systems and from 3D planes instead of 2D calculations from 3D reconstructions;
- our method is highly automated relative to other 3D methods, which reduces subjectivity and observer variability. This most likely explains the very good correlation coefficients for our method;
- our method takes into account the entire glenoid surface and entire scapula to calculate the respective planes, unlike typical methods that use only three points to define a plane;
- as far as we know, this is the first study of 3D radius of curvature on pathological, arthritic glenoids.

However our method has some weak points:

- it was not validated against a gold standard. In vivo measurements cannot be performed on our cohort of patients with shoulder arthritis;
- our method is feasible but much less automated when CT arthrography is used because the intra-articular contrast product and the cortical bone have similar

Table 3 Interobserver reproducibility.

	1st acquisition		2nd acquisition	
	ICC	95% CI	ICC	95% CI
Height	0.97	0.95 to 0.98	0.98	0.97 to 0.99
Width	0.98	0.96 to 0.99	0.98	0.96 to 0.99
Height at Max Width	0.95	0.90 to 0.97	0.97	0.96 to 0.99
Version	0.998	0.997 to 0.999	0.998	0.997 to 0.999
Radius of best-fit sphere	0.98	0.96 to 0.99	0.98	0.97 to 0.99

density. Our method could not be used with MRI images;

- our calculations do not take cartilage thickness into account, as cartilage is not visible on CT scans. The impact of this error is small, since the thickness of the remaining cartilage is much less in cases of glenohumeral osteoarthritis than with healthy glenoids.

Now that the validity of our method has been established, we can extend these glenoid morphology measurements to a larger cohort of patients with primary glenohumeral osteoarthritis. The goal is to adapt the design of current glenoid implant components, as needed, based on morphological data on a larger scale. This is especially worthwhile for the radius of curvature of the bone/implant interface. It should be as close as possible to the radius of curvature of the native pathological glenoid to preserve an optimal amount of subchondral bone during reaming. Our image processing methodology also allows us to continue developing tools to help with 3D preoperative planning, as some have already advocated [6,7], and tools for intraoperative navigation during total shoulder arthroplasty.

Disclosure of interest

Dr. Moineau has been asked by Tornier to speak at conferences.

Dr. Young has no conflict of interest.

Drs. Walch, Levigne and Boileau receive royalties from Tornier relative to prosthesis patents.

Dr. Levigne was employed as a consultant by Tornier to perform various measurements during this study.

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References

[1] Walch G, Young B, Mélis B, Gazielly D, Loew M, Boileau P. Results of the convex back cemented keeled glenoid component in primary osteoarthritis. Multicenter study with a follow-up > 5 years. In: Shoulder Concept 2010. Montpellier: Sauramps Ed; 2010. p. 117—30.

[2] Neer 2nd CS. Replacement arthroplasty for glenohumeral osteoarthritis. J Bone Joint Surg Am 1974;56(1):1—13.

[3] Churchill RS, Brems JJ, Kotschi H. Glenoid size, inclination, and version: an anatomic study. J Shoulder Elbow Surg 2001;10(4):327—32.

[4] Iannotti JP, Gabriel JP, Schneck SL, Evans BG, Misra S. The normal glenohumeral relationships. An anatomical study of one hundred and forty shoulders. J Bone Joint Surg Am 1992;74(4):491—500.

[5] Ganapathi A, McCarron JA, Chen X, Iannotti JP. Predicting normal glenoid version from the pathologic scapula: a comparaison of 4 methods in 2- and 3-dimensional models. J Shoulder Elbow Surg 2011;20:234—44.

[6] Hoenecke Jr HR, Hermida JC, Flores-Hernandez C, D'Lima DD. Accuracy of CT-based measurements of glenoid version for total shoulder arthroplasty. J Shoulder Elbow Surg 2010;19: 166—71.

[7] Nowak DD, Bahu MJ, Gardner TR, Dyrszka MD, Levine WN, Bigliani LU. Simulation of surgical glenoid resurfacing using three-dimensional computed tomography of the arthritic glenohumeral joint: the amount of glenoid retroversion that can be corrected. J Shoulder Elbow Surg 2009;18: 680—8.

[8] Scalise JJ, Bryan J, Polster J, Brems JJ, Iannotti JP. Quantitative analysis of glenoid bone loss in osteoarthritis using 3D computed tomography scans. J Shoulder Elbow Surg 2008;17:328—35.

[9] Scalise JJ, Codsi MJ, Bryan J, Brems JJ, Iannotti JP. The influence of three-dimensional computed tomography images of the shoulder in preoperative planning for total shoulder arthroplasty. J Bone Joint Surg Am 2008;90:2438—45.

[10] Walch G, Badet R, Boulahia A, Khoury A. Morphologic study of the glenoid in primary glenohumeral osteoarthritis. J Arthroplasty 1999;14(6):756—60.

[11] McGraw KO, Wong SP. Forming inferences about some intraclass correlation coefficients. Psychol Methods 1996;1:30—46 [Correction: 1:390].

[12] Shrout PE, Fleiss JL. Intraclass correlations: uses in assessing rater reliability. Psychol Bull 1979;86:420—8.

[13] Nyffeler RW, Jost B, Pfirrmann C, Gerber C. Measurement of glenoid version: conventional radiographs versus computed tomography scans. J Shoulder Elbow Surg 2003;12:493—6.

[14] Frankle MA, Teramoto A, Luo Z, Levy JC, Pupello D. Glenoid morphology in reverse shoulder arthroplasty: classifications and surgical implications. J Shoulder Elbow Surg 2009;18:874—85.

[15] Friedman RJ, Hawthorne KB, Genez BM. The use of computerized tomography in the measurement of glenoid version. J Bone Joint Surg Am 1992;74(7):1032—7.

[16] Kwon YW, Powell KA, Kwang Yum J, Brems JJ, Iannotti JP. Use of three-dimensional computed tomography for the analysis of the glenoid anatomy. J Shoulder Elbow Surg 2005;14: 85—90.

[17] De Wilde L, Defoort S, Verstraeten T, Speeckaert W, Debeer P. 3 3D-Ct scan study of the humeral and glenoid planes in 150 normal shoulders. Surg Radiol Anat 2011 [Epub ahead of print].

[18] Bryce CD, Pennypacker JL, Kulkarni N, Paul EM, Hollenbeak CS, Mosher TJ, et al. Validation of three-dimensional models of in situ scapula. J Shoulder Elbow Surg 2008;17:825—32.

[19] Lewis GS, Armstrong AD. Glenoid spherical orientation and version. J Shoulder Elbow Surg 2011;20:3—11.

[20] Wang H, Tang K, Gong J, Li J, Chen W, Xu J. Measurement and analysis of glenoid bony anatomy by use of three-dimensional computed tomography. Zhongguo Xiu Fu Chong Jian Wai Ke Za Zhi 2009;23(7):822—6.

[21] Budge MD, Lewis GS, Schaefer E, Coquia S, Flemming DJ, Armstrong AD. Comparison of standard two-dimensional and three-dimensional corrected glenoid version measurements. J Shoulder Elbow Surg 2011;20:577—83.

[22] Bokor D, O'Sullivan M, Hazan G. Variability of measurement of glenoid version on computed tomography scan. J Shoulder Elbow Surg 1999;8:595—8.

[23] Bryce CD, Davison AC, Lewis GS, Wang L, Flemming DJ, Armstrong AD. Two-dimensional glenoid version measurements vary with coronal and sagittal scapular rotation. J Bone Joint Surg Am 2010;92(3):692—9.

[24] De Wilde LH, Verstaeten T, Speeckaert W. Reliability of the glenoid plane. J Shoulder Elbow Surg 2010;19:414—22.

[25] McPherson EJ, Friedman RJ, An YH, Chokesi R, Dooley RL. Anthropometric study of normal glenohumeral relationships. J Shoulder Elbow Surg 1997;6:105—12.

[26] Mallon WJ, Brown HR, Vogler 3rd JB, Martinez S. Radiographic and geometric anatomy of the scapula. Clin Orthop Relat Res 1992;277:142—54.

[27] Von Eisenhart-Rothe R, Otto Mayr H, Hinterwimmer S, Graichen H. Simultaneous 3D assessment of gleno-humeral shape, humeral head centering and scapular positioning in atraumatic shoulder instability: a magnetic resonance-based in vivo analysis. Am J Sports Med 2010;38: 375—82.