Original article

Three dimensional scapular prints for evaluating glenoid morphology: An exploratory study[☆]

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ARTICLE INFO

Article history:

Received 29 April 2018

Accepted 7 June 2018

Available online 15 June 2018

Keywords:

3D printing

Shoulder replacement

Scapula

Glenoid

Retroversion

CT scans

ABSTRACT

Background: Computerised Tomography (CT) scans are conventionally employed to assess the glenoid morphology prior to total shoulder arthroplasty (TSA). This study explores the role of three-dimensional (3D) models for assessing glenoid morphology.

Methods: CT scans of 32 patients scheduled for TSA were reconstructed to scapular models using customised software and a desktop 3D printer. The size and aspect ratios were maintained. Glenoid version, glenoid maximum height and width, and the maximum acromion antero-posterior (AP) length were compared between the models and CT scans.

Results: The models were an accurate qualitative reflection of scapular anatomy. The average retroversion in 3D models was $8.19^\circ \pm 30.8^\circ$ compared to $10.26^\circ \pm 42.5^\circ$ in scan images. The mean difference was $2.07^\circ \pm 24.6^\circ$ ($p=0.408$). However, the mean absolute error was $5.02^\circ \pm 12.3^\circ$. The mean difference of the glenoid maximum width and the acromion maximum AP length was $0.22 \pm 3.33\text{mm}$ ($p=0.862$) and $0.32 \pm 14.12\text{mm}$ ($p=0.213$) respectively. However, the mean difference was significant for the glenoid maximum height measuring $3.67 \pm 12.04\text{mm}$ with $p=0.004$. The correlation between the examiners was high for all parameters, with intraclass correlation ranging between 0.94 and 0.99.

Conclusion: 3D printing technology promises to be a useful tool for preoperative planning with accurate reproduction of transverse plane anatomy. 3D prints represent superior definition of reconstructed anatomical measures such as glenoid height as compared to conventional CT Scans.

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1. Introduction

Accurate assessment of the glenoid dimensions and morphology should be performed prior to performing TSA.¹ Conventional plain shoulder radiographs are deficient in assessing the glenoid version and thus may misrepresent the accurate three-dimensional anatomy of the glenoid due to the scapula composition and its variations in positioning, the projection errors and the overlapping bones.^{2,3}

2D CT scans measure glenoid dimensions and version more accurately. However, the accuracy of the measurements depends on the position of the scapula at the time of obtaining the scan, since any rotation of the scapula may change the glenoid version by up to 10° .⁴ Hoenecke et al⁵ demonstrated that the use of CT scan prior to TSA is vital in the planning of this surgery. They found out

that 2D CT images are not as accurate as 3D CT reconstructions and recommended the use of the latter to fully assess the glenoid prior to TSA. Similarly, Kwon et al³ noted the advantage of using 3D reconstruction as it reflects the true shape and dimensions of the glenoid

Several studies have shown that glenoid component loosening is the most common mid-term and long-term complication of Total Shoulder Arthroplasty (TSA), leading to loss of shoulder function, shoulder pain and in some cases the need for revising the surgery.^{1,6} The glenoid version directly affects the humeral head displacement and the biomechanics of the glenoid component.⁷ Moreover, glenoid retroversion leads to increased asymmetric posterior load on the glenoid surface, which in turn leads to increased stress and micro-motion, negatively affecting the biomechanics of TSA and increasing the risk of glenoid component loosening.⁸ Therefore, glenoid retroversion correction is vital for the planning of TSA. This correction is usually achieved by eccentric reaming of the glenoid fossa during TSA surgery. This reaming is aimed to fulfil three main objectives: rectifying the glenoid version, creating complete contact between the prosthesis and the underlying bone, and maintaining adequate bone stock for secure

[☆] This study was awarded best Scientific poster at British Elbow and Shoulder Society meeting, 2015.

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glenoid embedding.⁹ However, excessive reaming of the glenoid may lead to significant bone loss, hence perforation and failure of the glenoid component.^{10,11} Retroversion can also be corrected by posterior cement adjustment or bone grafting which is recommended for retroversion greater than 15°.¹¹

Three dimensional (3D) prototyping is a cutting edge technology through which specialised printers produce a three dimensional replica of a previously prepared 3D digital design. Rengier et al.¹² summed up the stages of 3D printing in the context of medical imaging into three stages: The first is image acquisition that can be done by computed tomography, magnetic resonance imaging, ultrasonography and Positron Emission Tomography. The second step is image post-processing, where the acquired images are segmented using specialised 3D computer software, then changed into a format readable by the printer, such as Computer Aided design (CAD) software. The final step is 3D prototyping, where the scanned object is structured by ultra-thin layers of a material that is used to form the solid subject. This technology has been used in orthognathic surgery,¹³ as well as in neurosurgical¹⁴ and cardiovascular pre-operative planning.¹⁵

In this exploratory study, we used three dimensional printing technology to create scapular 3D models, using the CT scan images, of patients who underwent TSA. The aim was to explore how this technology can be incorporated into the pre-operative planning for TSA in assessing the glenoid morphology, and to compare results of printed scapular 3D models with the conventional CT scan.

2. Methods and materials

This research project was approved by the Research and Development (R&D) department at the Wrightington, Wigan and Leigh NHS Foundation Trust, UK. Thirty-five patients diagnosed with gleno-humeral arthritis, who had TSA performed in the Upper Limb Unit at Wrightington Hospital between January 2013 and December 2013, were retrospectively selected. Patients had CT scans done between May 2012 and September 2013 at Wrightington, Wigan and Leigh NHS trust. Patients who had previous glenoid fractures or had previous metal work were excluded since the former distorts normal glenoid anatomy while the latter distorts CT images. Thirty two out of the thirty five patients were eligible, seventeen males and fifteen females. Nineteen patients had CT scans done to their right shoulders, while the remaining thirteen had the scans done to their left shoulders. CT scan images were obtained with 1mm slice thickness.

2.1. CT scan measurements

The measuring tools in Centricity PACS systems (GE Healthcare) were used to measure the following glenoid parameters: the maximum glenoid antero-posterior length (AP length) corresponding to the distance between the most anterior to the most posterior glenoid surface point in the axial images; the maximum glenoid supero-inferior length (SI length) which was measured in the coronal oblique images and corresponds to the distance between the highest and lowest points of the glenoid fossa; the maximum acromion process antero-posterior length (AP acromion) measured in the axial images, covering the length between the most anterior to the most posterior point of the acromion; and the glenoid version which was measured in CT axial slides following the method described by Freidman et al.¹⁶ In this method the angle is measured in the axial views between a line drawn perpendicular to the scapular axis and a line representing the glenoid surface that is joining the anterior and posterior glenoid edges. These lines were drawn at the level of the mid glenoid which is determined at 10 slides below the level of the tip of the coracoid, since the CT slide thickness was 1mm.

2.2. CT images segmentation

CT scan images of the 32 patients were acquired in DICOM mode. The data acquired was then uploaded to Analyze 11.0 software, using the software's DICOM tool. The bone surfaces were then segmented by using a low threshold at 100 HU (Hounsfield units) and all low density pixels were filtered out. This allowed for the isolation of the bony structures (humerus, scapula, clavicle and scanned ribs) from the soft tissues. The scapulae were subsequently isolated from other bony structures by the "region grow" feature. These segmentations resulted in obtaining the 3D shape of the scapula as shown in Fig. 1.

2.3. 3D printing and models production

The obtained 3D digital models of scapula were changed into STerolithography (STL) format through Analyze software. This file format is supported by most rapid prototyping printers. The desktop printer used was MakerBot Replicator 2®, it uses Fused Deposition Modeling (FDM) technology. The material was Polylactic Acid (PLA) filament. In this technology, the filament is loaded into the printer. The nozzle is heated to a required temperature and

Fig. 1. 3D models in STL format after segmenting and rendering.

then a motor pushes the filament through the heated nozzle that makes the filament melt. The extrusion nozzle then lays down the molten filament on to the build plate layer by layer, where the filament cools down and solidifies. This technology is the most commonly used in 3D printing (Fig. 2).

2.4. 3D models measurements

Thirty-two models were generated by the 3D printer from the corresponding CT scans. Each of these models was measured for the maximum glenoid width which represents the maximum glenoid antero-posterior length in CT scan, the maximum glenoid height which corresponds to the maximum glenoid super-inferior length in CT, the maximum antero-posterior length of the acromion (This particular measurement was taken as a control measure as it is not affected by osteoarthritis and is obtained from axial images that did not require reconstruction), and the glenoid version.

A self-calibrated digital ruler was used for obtaining length measurements, and a self-calibrated digital goniometer was used for measuring the glenoid version on the 3D model.

Glenoid length measurements were obtained subsequent to stabilization of the printed scapulae. With respect to measuring the glenoid version, a scapula model holder was built following the same principles used by Churchill et al.¹⁷ This tool consisted of 2 wooden platforms (top and bottom) with exact dimensions, attached together by 2 identical wooden supports, one on each side at right angles, forming a rectangular box with 90° angles. Through the centre of each platform, a sharp threaded screw was introduced perpendicular to the corresponding platform. The screw tips touched precisely at their tips to ensure their co-linearity (Fig. 3A).

The printed 3D scapular model was then fitted within this frame, with the bottom screw going through the medial border of the scapula at the point it is joined by the scapular spine, and the top screw positioned in the centre of the glenoid. The model was positioned so that the inferior angle of the scapula was perpendicular to both platforms, allowing the inferior angle and the scapular axis to be co-planar (Fig. 3B,C). A self-calibrated digital protractor was then used to measure the version between the glenoid surface and the top surface as shown in Fig. 3D. Angles with the glenoid face directed posteriorly were recorded as retroversion; those facing forwards were recorded as anteversion.

All measurements were carried out by two examiners: a research clinical fellow in trauma and orthopaedics and a fellowship-trained orthopaedic shoulder surgeon.

3. Results

The independent-samples *t*-test was used to reveal differences in the means between the two independent groups for all measurements taken. The mean absolute error was recorded for the glenoid version between the two groups. The Intraclass Coefficient (ICC) test was used to test the reliability of the results between the two examiners (Table 1).

Friedman's approach was used to measure the glenoid version in CT scans, while that of Churchill et al was used for the 3D printed models. Friedman's method excludes the osteophytes of the glenoid. On the other hand, osteophytes were included when the 3D models were segmented and by measuring the glenoid version in these models the osteophytes were considered as margins of the glenoid, hence the glenoid version in CT scans was measured twice for each scapula, with and without the osteophytes. The glenoid version was not measurable in two of the CT scans because the glenoid surface at the level of the centre of the glenoid (10 slides below the level of the tip of the coracoid) was deficient in both of the CT scans, and the anterior and posterior edges of the glenoid could not be identified, hence it was not measured in the corresponding model. (Table 2)

The absolute error in the glenoid version was also measured between the 3D models and CT scans. The mean ($\pm$ range) of the absolute error between 3D models and CT with osteophytes was $4.96^\circ \pm 14.5^\circ$, and was $5^\circ \pm 11.2^\circ$ between 3D models and CT without osteophytes for measurement taken by the first examiner. Similarly, for the second examiner, the mean was $4.93^\circ \pm 15.2^\circ$, and $5.02^\circ \pm 12.3^\circ$ for 3D models versus CT scan with osteophytes and 3D models versus CT without osteophytes, respectively.

The results in all four parameters were consistent and reproducible between the two examiners as the ICC test has excellent results ranging between 0.94 and 0.997

4. Discussion

Glenoid component loosening is the most common complication of TSA leading to failure of this procedure.¹⁸ Osteoarthritis affects the morphology of the glenoid deforming its 3D structure commonly leading to retroversion of its antero-posterior axis.¹⁹ Several biomechanical research studies have shown that the correction of this deformity and placing the glenoid component in its accurate alignment is vital, as not doing so will lead to abnormal distribution of the loading forces on the glenoid component leading to early failure.^{20,21,22} Comprehensive assessment of the shoulder joint is vital prior to performing TSA.³ With any deformity that affects the 3D morphology of the glenoid, conventional

Fig. 2. Printed 3D models glenoid and posterior views.

Fig. 3. A: Glenoid version measuring tool showing that the top and bottom screws are co-linear. B and C: Position of the model for version angle measurement. Note the inferior angle in the same plane of the scapula axis. D: Measuring the model glenoid version.

Table 1
Glenoid dimension measurements in 3D model and CT scans (Mean $\pm$ range).

		Average measurements scapula 3D model	Average measurements CT scan	Difference in means (3D models versus CT scan)	P value
Maximum glenoid AP length	Examiner 1	36.26 $\pm$ 21.83mm	36.04 $\pm$ 22.84mm	0.22 $\pm$ 3.33mm	0.862
	Examiner 2	36.19 $\pm$ 20.22mm	35.62 $\pm$ 23.96mm	0.57 $\pm$ 4.45 mm	0.655
Maximum glenoid SI length	Examiner 1	46.96 $\pm$ 18.87mm	43.95 $\pm$ 20.72mm	3.01 $\pm$ 11.29mm	0.004
	Examiner 2	47.12 $\pm$ 18.89mm	43.52 $\pm$ 22.33mm	3.67 $\pm$ 12.04mm	0.017
Maximum acromion AP length	Examiner 1	46.86 $\pm$ 28.7mm	47.16 $\pm$ 23.88mm	0.32 $\pm$ 14.12mm	0.213
	Examiner 2	46.97 $\pm$ 30mm	47.13 $\pm$ 25.12mm	0.17 $\pm$ 17.54mm	0.914

Table 2
Glenoid version measurements in 3D models and CT scans (mean $\pm$ range).

	Average version scapula 3D model	Average version 2D CT with osteophytes	Mean Difference	Average version 2D CT without osteophytes	Mean Difference
Examiner 1	8.19° $\pm$ 30.8°	10.26° $\pm$ 42.5°	2.07° $\pm$ 24.6° (p = 0.408)	6.903° $\pm$ 35.6°	1.28° (p = 0.544)
Examiner 2	8.31° $\pm$ 30.4°	9.95° $\pm$ 42.4°	1.64° $\pm$ 25.8° (p = 0.509)	6.85° $\pm$ 36.7°	1.46° (p = 0.494)

methods of 2D imaging may not be sufficient or may even misinterpret the actual glenoid profile.^{2,3} Furthermore, the glenoid version depends on the position of the glenoid in the coronal plane which in turn is dependent upon the patient's position during the CT scan, as minor rotation may change the version angle by up to

10° when measured by a 2D CT scan.⁴ Therefore, several studies have recommended using 3D imaging to fully assess the glenoid.^{3,5}

This study compares the use of 3D prototyping technology against the conventional CT Scanning for studying glenoid morphology and parameters. Automatic segmentation was

sufficient in many of the cases. However, due to the arthritic changes in both the gleno-humeral and acromion-clavicular joints and the loss of the joint space, which led to the humeral head contacting the glenoid and the lateral end of the clavicle contacting the acromion, automatic segmentation was followed by manual segmentation to delineate the glenoid and the acromion boundaries. Processing each CT slide and deleting the bony edges that were not related to the scapula achieved this. This method is deemed to be the most employed method for segmentation,²³ and was validated and found to be accurate by Bryce et al¹⁸ and Spottiswoode et al²⁴ as the latter, in his experiment in printing out shadow objects from cerebrum MRI, discovered that the measurements of the printed models were very accurate with a mean dimensional error of 0.5 mm, $p=0.12$. This method, even though necessary, is very time consuming. However, A follow up study with a control group of patients with normal shoulder CT scans is recommended so the glenoid measurements can be compared between the CT scans and 3D printed models of this group.

For the glenoid maximum AP length there was not a significant difference in the measurements between 3D models and CT scan images, as the difference in the means was 0.22 ± 3.33 mm with $p=0.862$ and $0.57 \text{ mm} \pm 4.45$ mm with $p=0.655$ for the first and second observers respectively. Likewise, the difference was insignificant for the maximum acromion AP length, as the difference in the means calculated as 0.32 ± 14.12 mm, $p=0.213$ and $0.17 \text{ mm} \pm 17.54$ mm, $p=0.914$ for the first and second examiners respectively. These results showed excellent reliability and correlation as ICC ranged between 0.949 and 0.998. We believe that this is because these two parameters were measured in the axial images of the CT scans, and their images did not require any reconstruction, and also to the fact that 3D printing accurately reproduce the actual scapular dimensions since the control measure (acromion AP length) did not show significant difference between the two modalities.

However, for the glenoid maximum SI height, the length was measured from the reconstructed coronal oblique slides and the printed models proved significant difference between the two modalities. The mean difference was $3.01 \text{ mm} \pm 11.29$ mm ($p=0.004$) and $3.67 \text{ mm} \pm 12.04$ mm ($p=0.017$) for the first and second examiners respectively. The intraclass correlation test here showed excellent consistency and reliability between the observers with ICC = 0.95 for 3D and 0.97 for CT measurements.

The segmentation of the glenoid was performed while preserving the whole of the glenoid, including the arthritic changes, and that resulted in having glenoid fossae with arthritic changes including osteophytes for the 3D prototyped scapulae. It was not possible to measure the glenoid version in the 3D printed scapulae without the osteophytes as they comprised part of the surface. Hence, in order to compare the glenoid version between 3D printed scapulae and CT scans, the version was measured twice in CT scans, with and without osteophytes. Freidman et al¹⁶ method was used for measuring the glenoid version in axial CT images, it estimates the centre of the glenoid 4 slides (with 2.5 mm thickness of each slide) below the tip of the coracoid. However, there can be ethnic and gender variations in glenoid version as per Straus et al.¹ We did not take that into account whilst measuring the centre of glenoid, hence that is a limitation of the study. The results were reproducible and consistent between the two observers as the ICC was between 0.98 and 0.99. The difference in the means of the glenoid version was small and insignificant for the comparison done with and without osteophytes. The sample size is small, and this may explain this insignificant result. However, the sample size was limited with time consumption with creating the digital 3D models as segmentation time took between half an hour to 2 h for each scan depending on the amount of manual segmentation. Printing time took between 12–20 h for

each scapula model. The sample size was also limited with the cost factor of the printing materials. Another reason could be due to the fact that we did not compare the results with a control group of shoulders that are not affected by osteoarthritis. On the other hand, a difference was noted when comparing the version between the groups singularly, as the mean absolute error was around 5° when comparing the glenoid version between the two groups with and without osteophytes. Several biomechanical reports have associated glenoid version with humeral head subluxation and early failure of the glenoid component,⁸ and have recommended that a retroversion of 10° is disadvantageous for TSA and should be corrected,^{8,25} hence we believe that a difference 5° is significant for the preoperative assessment of the glenoid version. However, this needs to be further investigated in studies with larger sample size and with a control group of patients with normal shoulders. This was a retrospective study for patients for whom total shoulder arthroplasty has been performed. These models help better understand the individual glenoid anatomy, particularly the glenoid version. This can help better plan the glenoid preparation and implantation, such as the amount of reaming needed, or the need for bone grafting.

5. Conclusion

Three dimensional prototyping is a cutting-edge technology that creates identical replica of the scanned objects, and the printed 3D scapulae represented an accurate reflection of the scapular anatomical and pathological characters. This technology can be a valuable and practical tool for assessing the glenoid and measuring its version as it allows for direct visualisation of the scanned scapulae, even though generation of 3D models is currently time-consuming.

Funding

No financial bias exists.

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