

3D printing in shoulder surgery

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Abstract

Three-dimensional (3D) printing is a novel modality with the potential to make a huge impact in the surgical field. The aim of this paper is to provide an overview on the current use of 3D printing in shoulder surgery. We have reviewed the use of this new method in 3 fields of shoulder surgery: shoulder arthroplasty, recurrent shoulder instability and orthopedic shoulder traumatology. In shoulder arthroplasty, several authors have shown that the use of the 3D printer improves the positioning of the glenoid component, even if longer clinical follow-up is needed to determine whether the cost of this system rationalizes the potential improved functional outcomes and decreases glenoid revision rates. In the treatment of anterior shoulder instability, the literature agrees on the fact that the use of the 3D printing can: enhance the dept and size of bony lesions, allowing a patient tailored surgical planning and potentially reducing operative times; allow the production of personalized implants to restore substantial bone loss; restore glenohumeral morphology and instability. In orthopedic trauma, the use of 3D printing can be helpful to increase the understanding of fracture patterns, facilitating a more personalized planning, and can be used for resident training and education. We can conclude the current literature regarding the use of 3D printed models in orthopedic surgery agrees finding objective improvements to preoperative planning and to the surgical procedure itself, by shortening the intraoperative time and by the possibility to develop custom-made, patient-specific surgical instruments, and it suggests that there are tangible benefits for its implementation.

Introduction

With the increasing complexity of operations and surgical decision-making,

three-dimensional (3D) printing is a novel modality with the potential to make a huge impact in the surgical field. In 1984, the first patent for a 3D printer was filled in the United States by Charles Hall titled, "Apparatus for production of 3D objects by stereolithography", which was, in effect, the world's first 3D printer.¹ The first reported use in orthopaedics was in 1999 as an aid to preoperative planning in complex spinal surgery.²

Currently, in orthopaedics, the use of 3D printing can be broadly split into three categories. This includes: (1) pre-operative planning; (2) 3D implants; and (3) 3D patient-specific instrumentation (PSI). In pre-operative planning, 3D printed models can allow surgeons to visualise relevant anatomy and help aid executing complex operations.³ 3D printed implants can be used for direct replacement of a large defect after tumour resection and to aid reconstruction in limb-salvage surgery.⁴ PSIs can have a wide application across orthopaedics and can be largely used for more accurate implant placement, especially in the presence of abnormal anatomy and deformities, as well as developing templates for deformity correction and tumour resection.⁵

Whilst initially 3D products were used for complex cases, they are now becoming part of the routine, and this is likely to have a significant impact on all of our practices in the upcoming years, as they have been seen to offer several additional advantages. As an example, they can help in the training of novice surgeons in surgical areas that result complicated. Moreover, the model can also be examined again intraoperatively if necessary.^{3,6,7} A preoperative examination of the 3D model allows the surgeon to predict intraoperative difficulties, to select the optimal surgical approach, to plan in advance the correct implant placement, to identify the screw trajectory and the need for special equipment.

The aim of the present paper is to provide an overview on the current use of 3D printing in shoulder surgery.

3D printing: how does it work?

3D printing converts a computer-generated 3D image into a physical model.

3D model creation is based on 3D DICOM (digital imaging and communications in medicine) format data derived from computed tomography (CT) or magnetic resonance (MR). The DICOM files are therefore uploaded into a program (e.g., Mimics from Materialize for Windows, Osirix for Mac) which enables 3D

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Key words: 3D Printing, Arthroplasty, Shoulder Instability, Trauma surgery, Patient-specific instrumentation.

Contributions: the authors contributed equally.

Conflict of interest: the authors declare no potential conflict of interest.

Funding: none.

Availability of data and materials: Available on request

Ethics approval and consent to participate: Not applicable.

Informed consent: Not applicable.

Received for publication: 11 April 2020.

Accepted for publication: 17 June 2020.

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Orthopedic Reviews 2020; 12(s1):8681

doi:10.4081/or.2020.8681

reconstruction of the image. It is then exported to a file format (stereolithography [STL]) making it readable by a software (*computer aided design* - CAD) which is used to design 3D objects. 3D printers "additively manufacture" or create objects layer by layer.⁸

3D printing in shoulder arthroplasty

The number of shoulder arthroplasties has been constantly increasing since the beginning of this century.⁹⁻¹¹

The shoulder is a highly mobile joint, and its stability is a delicate combination of multiple factors, including bone orientation, ligamentous restraints, and periarticular muscle balance. With respect to shoulder arthroplasty, a malpositioning of the implant might be responsible for immediate postoperative complications, such as dislocation, as well as increased shear forces and a higher loosening rate in the long term.¹²⁻¹⁷

The glenoid component is generally considered to be the most problematic part in both anatomic total shoulder arthroplasty (TSA) and reverse total shoulder arthroplasty (RTSA), accounting for up to

30% of overall complications.¹⁸ In some cases, glenoid bone stock could be insufficient,^{19,20} or deformities can lead to excessive retroversion or inclination as well as glenoid vault perforation.^{21,22}

3D preoperative planning software and PSI are becoming gradually commercially more and more available as a guide in the insertion of the glenoid component in TSA and RTSA.²³

The process involves the use of standard preoperative CT scan images of the patient's scapula that are then uploaded and used to create a 3D model of the patient's glenoid. Manufacturer specific algorithms are then applied to the model and the glenoid component positioning is determined. The surgeon then reviews, adjusts where necessary, and approves the proposed plan using 3D planning software. The disposable, patient-specific drill guides and a bone model of the glenoid are then produced using rapid prototyping technology and are delivered for the surgical procedure.

Depending on the manufacturer, different types of guides are available to determine the insertion point and orientation of the central guide pin on the glenoid surface, as well as a further guidance of the reaming depth and angle. In RTSA, the rotation of the baseplate and the length and orientation of the screws can be accurately guided with selected PSI systems optimizing the final implantation of the glenoid component.²³ Regardless of the system used, it is essential that sufficient exposure of the glenoid is obtained, including the anterosuperior part of the glenoid rim, and that all soft tissues are removed before the PSI guide is positioned on the native glenoid. The PSI should have a stable fit onto the glenoid just like on the bone model. The surgeon's intuition remains cardinal in finding and double checking the ideal insertion point and orientation of the central guide pin and also the further execution of the glenoid preparation, positioning, and fixation of the component.

Several authors have shown that the use of the 3D printer improves the positioning of the glenoid component. In a study of Iannotti *et al.*,²⁴ on bone models, the accuracy of pin positioning using PSI compared with use of standard instrumentation increased by $3.7^\circ \pm 0.9^\circ$ in version, $8.1 \pm 1.2^\circ$ in inclination, and 1.2 ± 0.2 mm in location. Lewis *et al.*,²⁵ in 2015 affirmed that version and inclination errors using the pin array guide on polymer models of glenoids were significantly lower compared with no assistance. In a study of Walch *et al.*,²⁶ on cadaveric scapulae the mean error in 3D orientation of the guide pin compared with the preoperative planning was 2.39° , the mean entry point position

error was 1.05 mm, the mean inclination angle error was 1.42° and the average error in the version angle was 1.64° . Gauci *et al.*,²⁷ performed 17 TSA surgeries using PSI comparing the planned and the actual position of the entry point (mm) and orientation of the glenoid component. The mean error in the accuracy of the entry point was -0.1 mm in the horizontal plane and 0.8 mm in the vertical plane. The mean error in the orientation of the glenoid component was 3.4° for version and 1.8° for inclination. In the same way Berhouet *et al.*,²⁸ studied 10 patients who underwent TSA with use of a PSI to position the glenoid component after preoperative 3D planning. Mean errors in glenoid position were -1.7° for version, -0.4° for tilt, and 6.0° for rotation. Mean difference in global orientation of the glenoid implant versus the planned value was 4.9° . Mean 3D discrepancy in glenoid pilot hole position was 2.9 mm. Jacquot *et al.*,²⁹ in 2018 argued that PSI slightly improved the position of the central point but not the orientation of the component compared to the freehand method. They studied 17 patients who underwent TSA and the mean error for the central point was 2.89 mm with the freehand method versus 2.1 mm with use of a targeting guide, while the mean errors for version and inclination were respectively 4.82° and 4.2° with freehand method, compared to 4.87° and 4.39° with a targeting guide. In 2019 Cabarcas *et al.*,³⁰ randomized 20 cadaveric shoulders to receive pin placement via the PSI guide or standard TSA guide. For each specimen was created a presurgical plan from CT scans. The inclination deviation was significantly lower in the PSI group than in the standard guide group (1.5° vs. 6.4°). The glenoid entry site exhibited significantly less deviation in the PSI group (0.8 mm vs. 2.1 mm).

However, the technology did not completely eliminate variability due to the pure geometric nature of a PSI approach in general, not taking soft-tissue status into account. In some cases, the segmentation process of the bone in the software can or cannot remove calcified or ossified parts of the glenoid rim or anterosuperior labrum, and these same structures may or may not be removed by the surgeon at the time of the procedure.³¹

Nevertheless, longer clinical follow-up needs to determine whether the cost of this system rationalizes the potential improved functional outcomes and decreased glenoid revision rates.

It will be important to understand with further studies also what will be the role of computer assisted navigation in the future in shoulder prosthetic surgery.

3D printing in the treatment of recurrent shoulder instability

Recurrent anterior shoulder instability often results from glenoid and humeral heads bone defects, reason why a careful preoperative planning is essential. CT scan is nowadays considered the gold standard for bone loss evaluation.^{32,33} 3D CT scan in glenohumeral instability allows the 3D evaluation of both glenoid and humeral head defects. There are only a few studies documenting the use of 3D printing technology on the treatment of recurrent anterior shoulder instability in literature.³⁴⁻³⁶ They all agree on the fact that the use of 3D printing can have several advantages: enhancing the understanding of depth and size of bony lesions, thus allowing a patient tailored surgical planning and potentially reduce the operative times,³⁴ and the possible complications; allowing the production of personalized implants to restore substantial glenoid bone loss as well as glenohumeral morphology and bone stability. Sheth *et al.*,³⁴ in 2015, presented the case of a 29 year old man with a history of recurrent anterior shoulder dislocations, that had over 20 traumatic and atraumatic episodes of anterior dislocation or subluxation. In this patient the creation of a solid 3D model was successfully used in the preoperative planning stages of an arthroscopic Bankart repair and remplissage to determine the depth of the Hill-Sachs lesion and the degree of abduction and external rotation at which the Hill Sachs lesion engaged. Also Willemssen *et al.*,³⁵ in 2019, demonstrated the efficacy of the use of a 3D printed model. They created an anatomic specific titanium implant as a treatment option for recurrent anterior shoulder instability with substantial glenoid bone loss. They conducted a biomechanical study, in a cadaveric model, on ten fresh frozen human shoulders. They compared the anatomic-specific implant and the classic Latarjet procedure. Results showed that mean translational peak force after restoration with the anatomic specific implant was significantly higher than the intact state and comparable to the Latarjet procedure, with less variability noticed in 3D printed models, thus showing that 3D printed model can help surgeons to restore glenohumeral morphology and bone stability.

In contrast, Miyazaki *et al.*,³⁶ after producing 3D plaster models of Hill Sachs lesion obtained from CT scan of 14 patients with anterior shoulder instability, showed that there was no reliability for Hill-Sachs lesion measurements between plaster models and software models, thus arguing that a different method to assess the Hill Sachs lesion is still required.

3D printing in orthopedic traumatology

3D printing technology can find various application in the field of orthopaedic trauma; it provides a dynamic integration of digital industry technology and modern minimally invasive technology for orthopaedics. The following studies all show how the use of 3D printing technology can be helpful to increase the understanding of fracture patterns and regional anatomy, to facilitate preoperative and personalized planning, and can be used for resident training and education.³⁷ A definite advantage of 3D printed models is also the possibility to allow the simulation of difficult surgeries of orthopaedic trauma to advance practice.³⁸ It also potentially helps in shortening the time for surgery, and reducing blood loss volume. Moreover, it can help surgeons to make an individual, accurate, and reasonable surgical plan for patients.³⁹ You *et al.*,⁴⁰ in 2016, demonstrated how 3D printing technology has shown great clinical feasibility for the treatment of complicated proximal humeral fractures. Sixty-six old patients with persistent complicated proximal humeral fractures were randomly assigned to two groups, where the planning of the treatment was conducted either with 3D printing technology, or with a standard approach by using thin layer CT scan. The 3D printed models clearly displayed the fracture, thus helping the surgeons to determine the fracture classification and the magnitude of fracture injury, besides designing a careful preoperative planning.

Wang *et al.*,⁴¹ in 2018 also explored the clinical efficacy of 3D printing fracture models, used to assist in creating pre-contoured long helical PHILOS plates to treat proximal third humeral shaft fractures. They retrospectively identified 46 patients with proximal third humeral shaft fractures, allocated either to a Synbone group, or to a 3D printed group. Although the results of both groups showed that all fractures were healed and had satisfactory outcomes after 1 year, the 3D group showed immediate significant advantages in terms of duration of surgery, a reduced blood loss volume, and in making the surgical procedure easier for less-experienced surgeons. Chen *et al.*,³⁹ in 2018, compared three different approaches: 3D printing technology, computer assisted virtual surgical technology, and standard imaging. They aimed to compare: fracture characteristic identification, intraoperative realization of preoperative planning, and clinical outcomes. Patients in the virtual surgical and 3D printing groups had better overall outcomes than those in the conventional group. Both the techniques helped in making a more personalized

planning, and in better surgical outcomes. However, virtual surgical technology seemed to have some advantages over 3D printing technology since it required shorter time for preoperative planning and interval from injury to surgery as well as a shorter duration of hospital stay.

To sum up, current literature agreed on the help that 3D printing technology can give to the field of orthopaedic trauma, but further studies are needed to draw a definitive conclusion, especially in terms of cost-efficiency.

Discussion

The role of 3D printing in surgery has yet to be fully determined. Many fields are exploring the ways in which the technology can be employed.⁴² With regards to orthopaedic surgical planning, it is evident that the technology offers advantages.⁴³ When analysing the subjective data regarding the benefits of 3D models, there is a consistent trend that surgeons found 3D models useful when dealing with complicated anatomy.⁴⁴⁻⁵⁸ 3D printed 1:1 scale models allowed surgeons to appreciate the structure and relations of the relevant anatomy much better than the visualization provided by bi-dimensional (2D) CT images conventionally used today. Inspection of these models also revealed structural abnormalities not appreciated on CT which altered the surgical approach in a significant number of cases.^{47,48,51,56,59} These models can also be sterilized and taken into the surgical field to provide the surgeons with a template to review intraoperatively.^{46,60-62}

The current literature consistently showed that 3D model cohorts had shorter surgery times, lower volumes of blood loss intraoperatively and shorter fluoroscopy times.^{44,60,63-68} The ability to use the models to simulate the surgery allowed for planned placement of implants and selection of instrumentation, thus reducing the number of adjustments and the need to contour implants intraoperatively. Models were also used to evaluate the structural integrity of landmarks to which the implants are fixated.

Patients surveyed in the literature responded with enthusiasm regarding the use of 3D printed models. All patients felt that they better understood their injury and their upcoming surgery. Surgeons also felt that 3D printed models were a valuable communication tool when counselling patients. They felt having a tangible structure to show the patient the procedure they were about to perform was superior to all currently available media.^{60,63,66}

These 3D models have also shown to be useful in students' and residents' education, making them able to perform simulated surgery, and having also an effect on patient's safety, especially with inexperienced surgeons, instead of performing risky procedures directly on the patient.³⁷

While the current literature demonstrates that there are objective benefits to 3D printing in the field of orthopaedic surgery, further studies are required to examine what aspects of the technology contribute to this. Metrics such as time taken, cost-effectiveness, accuracy, training proficiency time and surgeon confidence should all be explored. The inclusion of soft tissue structures within anatomical models is another aspect with limited evidence.

Currently, limitations associated with this technology are mainly related to time required to create a 3D printed model and costs.⁶⁹ Hopefully, as 3D printing technology progresses both the cost and production time will likely be to reduce.

Conclusions

The current literature regarding the use of 3D printed models in orthopaedic surgery suggests that there are tangible benefits to its implementation. The technology offers objective improvements to preoperative planning and to the surgical procedure itself, by shortening the intraoperative time and by the possibility to develop custom-made, patient-oriented surgical instruments. However, further investigations aiming to optimize the process in order to short the time required and cost-effectiveness studies are required before the technology could become a routine part of planning complex orthopaedic procedures.

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