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Chapter 9

Using 3D-printed Patient-optimized Surgical Tools (3D POST) for Complex Hip and Knee Arthroplasty

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Additional information is available at the end of the chapter

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Abstract

Planning is a key step in all surgeries. Well-planned cases have better outcomes than the unplanned ones. The conventional planning used to be done on radiographs and other imaging. Three-dimensional (3D) printing using additive manufacturing process has taken this a step further. The process involves converting the radiographic digital formats into machine-printable format. The three-dimensional model is typically made of a plastic material that allows surgical simulation.

In complex arthroplasty, especially those such as revision scenarios or difficult primary cases such as dysplastic hips, protrusio, fused, or posttraumatic arthritic hips, these models serve as an invaluable tool in planning the surgery. They help reduce inventory by facilitating optimal implant and instrument ordering, and also serve as intraoperative referencing. By performing surgical simulations preoperatively, the surgeons can rehearse their surgical steps and also decide upon the implant type and accurate implant placements.

Keywords: Knee Replacement, Hip Replacement, 3D Printing, 3D POST, Patient-Specific Instruments (PSI), Implants

1. Introduction

Preoperative planning for complex arthroplasty was always a challenge for orthopedic surgeons. Various factors that needed to be considered included choice of joint replacement implants, need of the bone graft, optimal exposure and approach to the same, trauma implants, and postoperative assessments. The availability of computed tomography (CT) scans and software-based reconstruction provided very versatile tools in the hands of the surgeons.

Medical rapid prototyping (RP) is a new concept that is borrowed from the industrial designing concept. The idea of layered manufacturing was evolved in industries to form a part using

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sequential addition of layers of a material. The modern computer-aided designing (CAD) program ensured rapid production of a component with unmatched accuracy [1]. This concept was then adopted in the medical field, which had an advantage of an accurate cross-sectional representation of the body part that was obtained using modern imaging methods such as CT scans. These images were converted to suitable industrial designing formats using a specialized software and then 3D printed. The 3D-printed models also known as biomodels provided a unique opportunity in preoperative planning, surgical simulation, intraoperative referencing, and postoperative assessment.

The power of physical objects over drawings and illustrations is well established. The prototypes have been used since ages and their role in the medical field is equally well established. Previously, for deformity correction, surgeons used to employ the artists and cast makers to recreate the exact anatomy. In the early 20th century, the surgeons would keep the representative model of the bone from cadaver to help in orientation during surgeries [12]. 3D printing and rapid prototyping has transformed these intraoperative measures by giving surgeons an accurate model of the patients' injury pattern and anatomical representation (Fig. 1).



Figure 1. Model being printed on 3D printing machine.

2. Challenges of complex arthroplasty

Hip arthroplasty: The challenges of complex primary hip arthroplasty (dysplastic hip, ankylosing spondylitis, protrusio, postfracture reconstructions) and revision hip arthroplasty

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include assessing the bone defect and reconstructing the same. The primary goal is optimal placement of the acetabular component in the anatomic position, equalizing leg lengths, preserving, augmenting or restoring pelvic bone stock, and ensuring a stable fixation.

Knee arthroplasty: Similar to hip arthroplasties, cases with bone loss, post-traumatic arthritis, severe deformity, and revision scenarios are challenging for a joint replacement surgeon. In order to achieve an optimal outcome, he must plan and work accordingly. Careful assessment using all techniques and imaging available is of paramount importance.

In surgery, preoperative planning plays a vital role in, where the outcome of any surgical procedure critically depends on how well the surgeon and his team prepare for the surgical intervention at their end. The first generation of preoperative planning involved a pencil and paper approach wherein surgeons hand-traced physical radiographic images. These paper- and pencil-tracing methods suffer from distinct disadvantages of using two-dimensional imaging of three-dimensional configurations and extrapolating the same to develop a surgical tactic [2]. However, with time, these physical radiographs disappeared and digital planning systems evolved. The digital planning system allowed manipulation of radiographic images and the application of a wide variety of digital templates. There have been rapid strides and developments in the field of digital imagery and planning software based on CT. These second-generation techniques subsequently evolved and the surgeons and developers implemented ingenious techniques to use the standard image analysis software such as Adobe Photoshop (Adobe Systems, San Jose, California) to carry out digital planning for deformity correction. Although the second generation is an improvement, it did not offer a complete solution to the above mentioned drawbacks of the first-generation methods. The surgical preoperative planning involves several procedures including envisaging the end results, formulating an intraoperative strategy (usually a step-by-step flowchart), and arranging logistics (operating room environment, desired surgical inventory, technical personnel, and imaging). Conventionally, these processes were carried out based on patient's clinical condition and preoperative imaging studies. The preoperative imaging comprised of X-rays and CT scans, until 3D printing evolved into a necessary tool in difficult scenarios.

3D printing: 3D printing is known by several names – rapid prototyping, additive manufacturing, or layered manufacturing. Three-dimensional printing is considered one of the landmark developments toward the end of the last century. It has transformed manufacturing in general but specifically in the areas of aerospace, architecture, and fabrication industry. The three-dimensional printing process includes additive manufacturing or layered manufacturing, which involves assembling multitude of cross sections of a part in a layered or stacked position. The advantage is that, each cross section is extremely detailed and is positioned accurately in relation to its corresponding surrounding structure [3]. Another advantage of this additive manufacturing is that, for hollow parts or parts with varied density as in the case of human body parts, the entire piece can be manufactured in a single piece unlike the subtractive technology where the exterior and interior part may need to be produced separately.

Surgeons are increasingly using the 3D patient-optimized surgical tool (3D POST) in diverse fields such as orthopedics, joint replacement, maxillofacial surgeries, as well as neuro and spine

surgery. In orthopedics, 3D POST is used in the management of complex primary hip replacement, fractures, and revision arthroplasty cases.

These models are then used for surgical simulation preoperatively and as reference intraoperatively. These models have proven to be of a great help in preoperative planning, reducing surgical time, blood loss, and improved postoperative outcomes. In complex cases, such as difficult primaries and revisions, 3D POST aids in proper inventory planning as well as deciding and sculpting bone grafts. When done postoperatively, it can provide valuable information about the component positioning. The technique also provides data to develop patient-specific instruments and implants similar to those popular in knee arthroplasty. While performing simulation studies, data pertaining to the contact site and the supporting area of the host bone can also be obtained [4].

3. 3D printing technologies available

Fused deposit modeling: This is the most common technology available to surgeons and is also called additive manufacturing. In this method, a spool of the thermoplastic substance is inserted into an extrusion head that heats the material into a semisolid state. The extruder head then extrudes this semisolid thermoplastic or similar material. Specialized software converts the axial image into a machine-printable language that the machine presents layer by layer as a replica of the axial cuts.

Direct digital manufacturing: In this case, the device directly creates the end product. This printed product is ready to be used as the machine prints the material that is fit for end use. In the medical field, it could be the implants made from innovative materials such as titanium and tantalum and also bioceramics such as hydroxylapatite and tricalcium phosphate [5]. Having this technology at hand ensures a customized product for patients; this could be wedges, spacers, prosthesis, or artificial bones for defects. The technology enthusiast believes that in future most prosthesis and implants available would be made using this technology.

Polyjet: This technology helps to create highly precise parts and has an added advantage because of its ability to combine different materials and colors. In a way similar to the inkjet printers used in day-to-day life, these printers can help create models with over thousand physical properties and colors

4. Key areas where 3D printing is likely to play an important role in surgery

Preoperative assessment: A real life-sized model ensures that the surgeon can get a look, feel of the disease pathology in the entire three dimension. This is especially useful for orthopedic surgeons, joint replacement surgeons, cardiac surgeons, and maxillofacial surgeons [6]. The technology has a special use for oncology surgeons who can plan optimal resections and reconstructions (Fig. 2–5).

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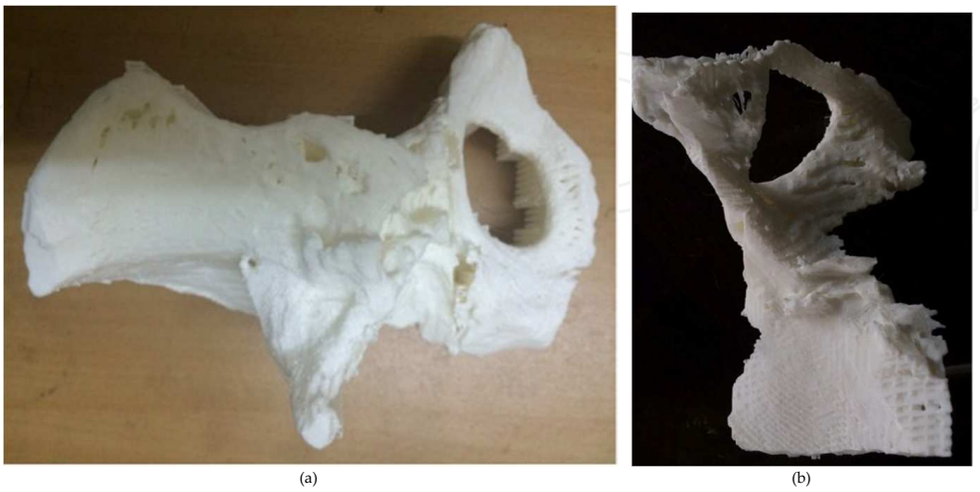
Figure 2. Preoperative simulation with reamers.



Figure 3. A model demonstrating the anatomy of the acetabulum with bone defects and areas of good bone stock.



Figure 4. X-rays of revision case whose planning was done using the 3D-printed biomodels



(a) (b)

Figure 5. (a) 3D-printed biomodels of the case. (b) 3D-printed biomodels of the case.

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Surgical simulation: As a next step, the surgeon can plan and also actually execute the surgical steps on a 1:1 model of the patient. They can choose correct implants, define their placements, and also look for any possible errors. Something like a heat phase of any race, it familiarizes the surgeon to what they can anticipate once the patient is opened up (Fig. 5–8).



Figure 6. Intraoperative pictures of the same case.

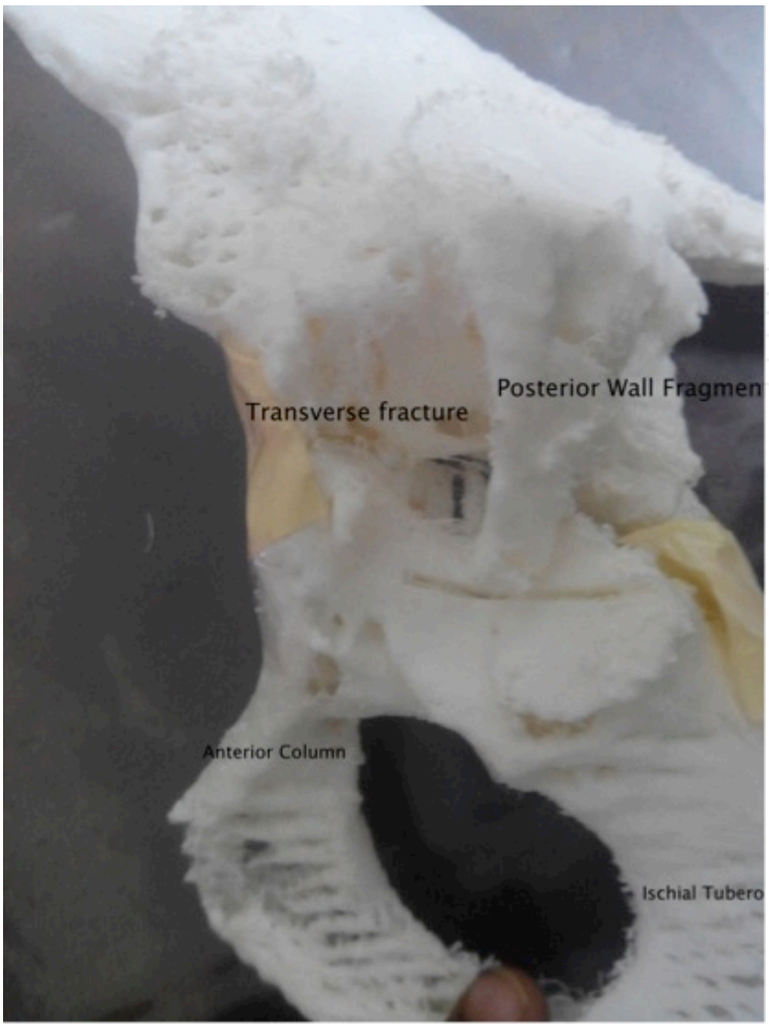


Figure 7. 3D-printed model of another case with posterior wall fracture.

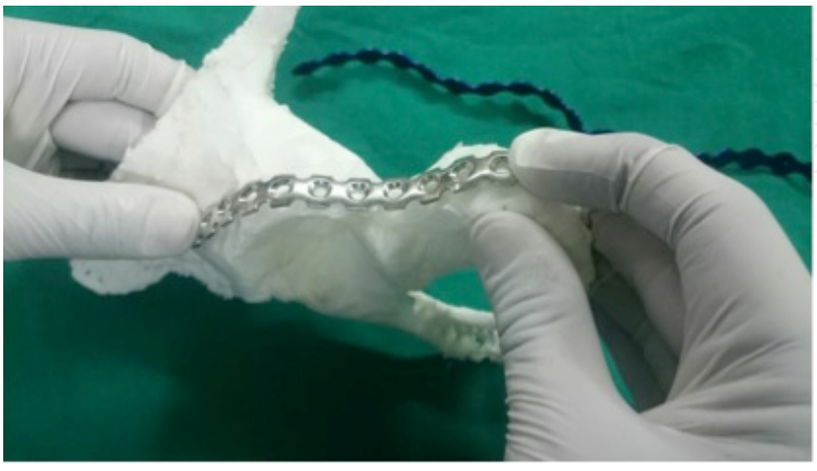


Figure 8. Reconstructing the posterior wall on the model using a reconstruction plate.

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Intraoperative reference: The model can be sterilized and kept on the operating table. The model can serve as a ready reference whenever the surgeon tries to accomplish a critical step. One can compare the actual pathology and surgical plans in this model.

Inventory management: Surgeons can plan for the implant – routine as well as specialized. This reduces the work of the operating room (OR) staff, increases turnover time of the operation room, and also reduces infection rates and improves overall system efficiency.

Customized (Patient Specific) instruments: The technology has made great headway in designing patient-specific instruments. Once the planning and simulation are done at the back-end office, appropriate jigs and cutting tools can be made using rapid prototyping [7, 12–14]. Several companies are aggressively developing this technology; and several proprietary devices such as Signature by Biomet and Visionaire by Smith & Nephew are currently available internationally (Fig. 9).



Figure 9. Intraoperative picture using 3D-printed customized jig in a case of total knee replacement (PSI-TKR).

Customized implants: In the near future, instead of one-size-fits-all implants, tailor-made implants will be used for individuals and specific pathologies. Not only will this increase the life of the implant and offer better kinematics but it will also ensure that natural non-damaged

parts are retained. ConforMIS is already available for limited use as patient specific implants in the US of A

Teaching tool: Traditionally, medical students learn normal anatomy on cadavers. However, this technology enables to study the diseased or fractured part in real-time. Surgical residents will benefit from the ability to simulate the surgery preoperatively on these models.

Patient education: Apart from acting as a teaching tool for the surgical residents and fellows, the 3D-printed models may also serve as an invaluable patient education resource. The patients can understand their disease process, planned intervention, and be a part of informed decision making. This is especially relevant for the interventions wherein the technical details may be overwhelming to the patients and relatives.

5. MRCP protocol: Medical rapid prototyping CT protocol

A good-quality CT scan with clear bone edges and details is essential for a good 3D print and rapid prototyping. A protocolized approach described below helps to ensure that all scans are usable and that the delay in processing and production is minimized [8].

Pre-CT scan guidelines: It is important that all standard guidelines for performing a CT scan be followed. This includes removing any metal jewelry, non-fixed implants, zippers, or any other artifacts that may cause distortions during the scanning process. It is important that the patient is made comfortable and his/her vitals are monitored throughout the procedure. The patient should be briefed about the planned procedure and any queries should be answered. He should be specifically asked not to move during the procedure.

Positioning: Patient is usually placed supine with arms by the side. The position may differ depending on the area of interest. Sometimes, a marker may be placed on the contralateral side for comparison and identification – calibration. The table height should be adjusted and the area to be scanned centered in the scan field. This position should not be altered during the scanning process. Operator should also ensure that there is no gantry tilt [9].

6. CT protocols

CT protocols are described as follows:

- *Field of view (FOV):* This is the region of interest and typically a small FOV measuring 12 inches × 12 inches is enough for most cases.
- *Scout:* This depends on the region of interest and helps planning.
- *Region of interest (ROI)* should be identified
- *Kv:* Automatic
- *mAs:* Usually automatic

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- *Pitch:* Ideally 512 × 512
- *Collimation:* 1.25–1.50 mm
- *Slice thickness:* Ideally 1.0–1.5; less than 2 mm
- *Slice increment:* Ideally 0.625–0.75; less than 1.0 mm
- *Kernel/algorithm:* Moderate/soft tissue (DO NOT use 'bone/detail')

7. Other tips

A typical image set includes "only one localizer image and three sets of axial images".

No need for secondary or 3D recon images, viewer softwares, or reformats; axial 2D images are sufficient.

- Ensure that there is no obliqueness/gantry tilt.
- Do not reformat in coronal and sagittal planes.
- Do not perform any lossy compression.
- Always retain a copy of permanent archives (PACS) of raw data.

8. Limitations

As is with any new technology, there are some drawbacks of 3D POST, PSI and 3D models. The foremost being the time taken for the production of these models, which is between 24 to 48 hours. Although not very significant, these can delay surgery, specially when the case has a priority status. However, most of the time, given the fact that these are planned cases, one can procure them without any major hassles [10].

The other issue that crops up is that of cost. These models cost more than a normal CT scan. The cost is usually US$ 100 in addition to the CT scan. However, once again, as initial studies have proven, these are clearly offset by decrease in surgical time, blood loss, and most importantly improved accuracy resulting in better outcomes.

9. Future

There is continuing improvement in this field. The future developments that are on the horizon include being able to print the models with different bone density gradients. These would give surgeons an insight on where and how the bone stock is likely to fare under load and identify the best bone for implant and screw placement. Printing various types of metal and biocompatible materials is likely to pave way for newer generations of biocompatible implants [11].

10. Conclusion

A recent addition to these existing techniques is prototyping or 3D modeling. In view of their ability to be specific to a patient, they are also called patient-optimized surgical tools or POST. The process involves converting the CT scan images into a machine-printable language. These inputs are then transmitted to a 3D printing machine, which using the additive manufacturing technology, creates a life-sized model. The model can then be used to perform preoperative planning, surgical simulation, intraoperative referencing, and outcome assessment.

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