Advances in 3D Modeling: Preoperative Templating for Revision Wrist Surgery

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Abstract

Background: Three-dimensional (3D) printing is a computer-directed process leading to the layered synthesis of scaled models. The popularity and availability of the technique has exponentially increased over the last decade, and as such is seeing a greater number of medical and surgical applications. **Methods:** We report 3 cases involving the use of 3D printing as an aid to operative planning in the revision of wrist surgery. **Results:** All patients underwent successful operative interventions with a £34 average cost of model creation. **Conclusions:** A growing number of reports are emerging in reconstructive surgical specialties including maxillofacial, orthopedic, and plastic surgery; from our experience, we advocate the economically viable use of 3D printing for preoperative templating.

Keywords: trauma, planning, 3-D, reconstruction, templating

Background

Additive manufacturing and rapid prototyping are widely used synonyms for the process of 3-dimensional (3D) printing; this growing technology is evolving to change the manufacturing industry, and over the last decade has had specific effects on surgical practice. The process first pioneered over 30 years ago¹² allows the creation of 3D objects through the successive deposition of material in 2-dimensional (2D) layers; subsequently, patient data can now be converted into custom prototypes/models.

The 3D printing has been documented as an effective adjunct for preoperative planning in maxillofacial and cardiac surgery^{10,15}; while cases are now also emerging of its utility in complex orthopedic cases typically in the context of revision arthroplasty, pelvic fractures, and tumor resections.^{11,17,19} As such, the development of this technology is now being reported in wider subspecialties, namely, upper limb and spinal pathologies.^{1,3,16} Although computed tomography (CT) and magnetic resonance imaging (MRI) are excellent for their diagnostic value, 3D printing may help better define anatomical relationships and aid surgical approach. In this study, we present our experience using computer-aided design/manufacturing (CAD/CAM) and 3D printing for preoperative planning in hand and wrist surgeries, a methodology that allowed an affordable, personalized, and rapid template prior to surgical intervention.

Case Report

The process of creating a 3D model from patient data has drastically simplified since first use.^{12,18} From Data Imaging and Communication in Medicine images (DICOM), a 3-step process was followed to create data suitable for printing: (1) *Segmentation* extracts the region of interest from the image data; (2) *transformation* adapts the volumetric data to a 3D mesh; and finally (3) transfer of the data to the compatible printer.

CT scans of each patient were taken at 1 mm slices (Figure 1) and saved in a DICOM format. Postprocessing segmentation was used to isolate the specific region of interest, and generate a surface mesh. Using a threshold tool, only the data within a set range of values were retained, thus concentrating the final image to density values of bone. Subsequently, these volumetric data were converted into a series of triangular facets using automated algorithms to generate a surface mesh, prior to exportation for 3D printing. Selective laser sintering (SLS) uses a fine powder of nylon and multiple metal alloys, fusing these powder

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Figure 1. Preoperative computed tomography image demonstrating ulna nonunion.

Figure 2. Sterile 3-dimensional printed polyethylene model.

substrates with a high-powered laser beam. A thin layer of the powder is sintered by the focused laser into the 3D shape; this process was then repeated layer by layer to replicate the complete desired anatomy in polyethylene. This rough model then underwent postprocessing to smooth surfaces and remove excess material (Figure 2). The process from image acquisition to polyethylene model creation cost on average £34 taking 6 working days.

Over a 3-month period, 3 patients were prospectively included in the study at our tertiary referral center. Patient A was a 25-year-old male who underwent acute open reduction internal fixation for a dominant-hand scaphoid fracture. Fifteen months post primary procedure, the patient complained of ongoing pain worsened on dorsiflexion of the wrist with a reduced grip strength compared to the contralateral side. Subsequent plain radiographs and CT on presentation to our unit revealed a malunited fracture requiring

Figure 3. Preoperative radiograph demonstrating metalwork position and ulna nonunion.

revision. Patient B was a 32-year-old right-hand-dominant male, who sustained an intrarticular distal radius and ulna fracture. Having undergone volar plating to the radius, he presented 23 months later with aseptic peri-implant osteolysis and an ulna nonunion (Figure 3). Patient C was a 46-year-old right-hand-dominant male with a history of rheumatoid arthritis and chronic high-dose steroid use. Due to joint degenerative changes, he underwent wrist arthrodesis in 2006; this was revised in 2009 due to chronic pain, with a concurrent radial styloidectomy and excision of scaphoid tubercle. A subsequent fall in 2011 required third metacarpal fixation, though this progressed to a nonunion by 9 months due to metalwork failure. Subsequently, 46 months following the failed primary arthrodesis, he underwent imaging and 3D modeling prior to elective revised fusion and fracture fixation (Figure 4).

All patients underwent near-isotropic-axial orientated CT scanning with 1-mm-thick slices. The virtual skeletal models were used for preoperative planning to determine resection and reduction; moreover, the 3D models aided appropriate metalwork selection, sizing, and orientation, allowing for the accurate precontouring of plates outside of the operating room, as well as helping plan surgical approach (Figure 5).

Printed 3D modeling was possible in all cases, plate fixation and orientation intraoperatively correlated well with preoperative plans. All patients had gone on to asymptomatic fracture union without complications at last follow (range, 6-12 months) (Figures 6 and 7).

Discussion

The 3D printing has demonstrated value in the preoperative planning of multiple procedures in a number of medical fields; subsequently, its use within orthopedics in the context of unpredictable and often altered anatomy is a logical

Figure 4. Preoperative radiograph demonstrating metacarpal nonunion after failed arthrodesis.

progression.^{2,5,13,15} The presentation of patients for elective revisions surgery after multiple failed procedures, as with Patient C, often renders CT and/or MRI imaging insufficient to fully appreciate anatomical variations, it is within this context that 3D printing has clear efficacy, aiding the planning of procedures and fabrication of metalwork and/or instruments where necessary.⁹ In addition, for elective procedures that may not require extensive resection or osteotomy, as with Patient B, 3D printing still provides an economically feasible adjunct to traditional preoperative planning tools.

Although we present one of the first cases using 3D modelling in hand and wrist surgery, cases have demonstrated its successful use in other orthopedic subspecialties. Tam et al¹⁷ presented the use of 3D printing in the reconstruction of a pediatric scapula osteochondroma, ultimately aiding in lesion resection and anatomic realignment. Similar to our experiences, by acquiring patient-specific anatomical knowledge, spatial relationships to surrounding structures were best appreciated, while simulation minimizes the occurrence of intraoperative complications. In addition to aiding surgical approach and intraoperative strategy, the economic benefits of 3D modeling cannot be overlooked. Potential cost-saving

Figure 5. Intraoperative image of ulna plating, patient B.

Figure 6. Three-month postoperative radiograph, patient C.

methods include reduction in operating time, personalized and sterile models, and the availability of these models within short time frames. The reducing cost of 3D printers and the increasing utility of the technology have rendered their use feasible despite tightening budgetary constraints.^{4,6} The use as a preoperative planning tool is not confined to delineating

Figure 7. Twelve-month postoperative radiograph after repeat ulna and radius plating.

just bony anatomy; Condino et al⁵ used 3D printing to recreate the complex neuroanatomy and soft tissues within the abdominal cavity. As such, these patient-specific tools allow for greater planning accuracy, and procedure simulation than traditional 2D imaging. Similar to the reported uses of 3D printing in maxillofacial surgery, we experienced particular benefit from the ability to precontour plates based on patient-specific 3D models. It is this aspect of the method that may prove increasingly amenable to orthopedic application, with the manufacture and contouring of implants for complex trauma and revision surgeries occurring far in advance of the patient being anesthetized.

Similar to the preoperative use of 3D printing, the creation of models to aid surgical teaching and simulation training is also significant. Among others, Niikura et al¹⁴ employed the use of 3D printed models as a means of patient education, using models as a tool when obtaining consent for acetabular reconstructions. Although printed models do not provide tactile stimuli in relation to tissue handling and surface topography, they do allow trainees and patients alike to fully appreciate bony anatomy and practice surgical approaches.

Our use of additive manufacturing to aid preoperative planning merely touches on the scope of this technology. Manufacturing flexibility, rapid production, and the ability to create complex structures of variable surface properties allow for the creation of 3D printed orthopedic implants be they from polyether ether ketone or porous tantalum. As such, although economic implications are significant, the ability of 3D printed prosthetics to accurately fit defects necessitates the consideration of this technique in complex cases. Moreover, Zimmerman and Moghaddan²⁰ crucially illustrated the ability of additive manufactured implants to slowly elute heat sensitive antibiotics, thus highlighting

their possible application in the treatment of periprosthetic infections as economically viable patient-specific spacers. In addition to implant manufacture, animal studies have alluded to the application of 3D printing to produce osteoconductive bone substitutes. Initial outcomes using these grafts be they calcium phosphate or hydroxyapatite composites have exhibited promising results, with significant increases in bone regeneration in critically sized long bone defects⁸. Concurrently, Fedorovich et al⁷ used 3D printing to create heterogeneous scaffolds containing accurately dispersed chondrocytes and bone marrow cells in mice, leading to tissue formation and the formation of extracellular matrices.

Our experiences using 3D printing in the preoperative planning of hand surgeries alludes to the broad applications of this evolving technology; prior to surgery, 3D printing may also heavily impact simulation training and surgical education. Intraoperatively, 3D printed instruments and prosthetics allow the financially viable creation of patient-specific tools that are not only anatomically accurate but also have a fabrication and delivery timescale within a matter of weeks. Ultimately, 3D printing has become a low-cost technique that has far reaching implications for orthopedic surgery specifically; indeed as the technology advances, additive manufacturing may progress to become integral in many orthopedic practices.

Ethical Approval

This study was approved by our institutional review board.

Statement of Human and Animal Rights

All procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation (institutional and national) and with the Helsinki Declaration of 1975, as revised in 2008.

Statement of Informed Consent

Informed consent was obtained from all patients for being included in the study.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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