Title Page

Title: Three Dimensional Printing in Orthopaedic Surgery: Review of Current and Future Applications

Short Title: Three Dimensional Printing in Orthopaedic Surgery

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Abstract

Three-dimensional (3D) printing is a rapidly evolving technology with the potential for significant contributions tosurgical practice. There are many current applications for 3D printed technology with future applications being explored. This technology has applications in preoperative planning, education, custom manufacturing (implants, prosthetics and surgical guides) and exciting potential for biological applications. This article reviews the current and future applications of 3D technology in orthopaedic surgery.

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Introduction

3D technology was first introduced two decades ago, when it was seen as unobtainable, expensive, and futuristic with limited clinical application [1-3]. In recent times there has been an explosion in 3D printing technology applications. Its use is becoming more widespread in surgery and the technology will likely play a pivotal role in orthopaedic practice.

What is 3D printing?

Three dimensional printing convertsa computer generated 3D image into a physical model. It is also referred to as rapid prototyping or additive manufacturing [4]. The object is built one thin layer at a time. Typically the manufacture of 3D models can be based on 3D Digital Imaging and Communications in Medicine (DICOM) format data from CT or MRI images.

The printer builds the model by a series of cross sectional layers of either liquid, powder or sheet material such as plastics/polymers and metals. The final shape is created when the layers are joined [4]. This process can be used to create unique patient-specific materials and may be more cost effective than conventional manufacturing of implants[5]. 3D printing can create any complex shape and allows solid and porous sections to be combined to provide optimal strength and performance [4]. Numerous different materials are utilised including plastics, polymers, glass, ceramic, metals [4, 6, 7] and biological materials [8].

Educational Applications

Three-dimensional models can be used to educate patients, students, trainees and surgeons. The visual 3D model can play an important role in the discussion and consent process for complex surgical cases. The model assists in demonstrating the complexity and severity of injuries to the patient and family, as well as help understandthe nature of the procedure. These models can thenalso be used for teaching students and trainees [9, 10].

Surgical Planning

Currently, 3D printing widely available in surgical planning for a variety of orthopaedic procedures. These cases vary from complex fracture patterns to revision arthroplasty surgery.

Three-dimensional printing is especially useful in complex trauma cases. The 3D printed models provide a visual and tactile aid in conceptualising complex fracture patterns [11]. The model can be sterilised andreviewedintra-operatively as required[12, 13]. Preoperative review of the 3D model can allow the surgeon to anticipateintra-operative difficulties, selection of optimal surgical approach and the need for specific equipment. Challenging pelvic fractures provide an example of these concepts (Figure 1)[13-17].

Paediatric orthopaedic surgeons [12, 18] have utilised 3D printed models to assist in the management of complex spine scoliosis, coalition in the foot, Perthes and Blounts disease. The models were used to assist in preoperative planning, communication with the patient, for reference during surgery with reported improvements in the safety of the procedure and reducing operative time.

Simple and complex osteotomies can be planned using models preoperatively. The surgeon can study the deformity and plan the surgery with a computer model. This includes the exact placement of implants and the ideal osteotomy site. 3D printing can produce jigs to allow for predrillingof holes for customised plates withbuilt-in osteotomy guides(Figure 2)[19].

There are published examples where 3D technology has been utilisedin complex cases of upper limb[20-27] and lower limb osteotomies[19, 28][29]. These articles support the notion that this technology simplifies complex surgery, providing confidence that goals of surgery are being achieved and reduce operative time. Trials comparing routine preoperative planning with the use of 3D printing are required [30].

Preoperative computer-assisted planning and custom 3D printed guides have also been described in pedicle screw placement [31], mosaic arthroplasty [32] and musculoskeletal tumour excision [33, 34].

In Australia the 3D printed guides that have been discussed are readily available, however cost is an issue. Typically these guides do not have a rebate from either Medicare or insurance companies, as they are not implantable devices. The cost can be up to $2000 AUD.

Most implant companies have 3D printed guides available to assist in standard knee joint arthroplasty [35]. A guide to assist with hip resurfacing has been described [36]. This process is commonly called Patient Specific Instrumentation (PSI). Patients have either CT scan or MRI scan to produce DICOM images. 3D images are then created and a preoperative surgical plan constructed to achieve perfect implant placement. Disposable cutting blocks are then fabricated to match and conform to the patient's anatomy using 3D printing technology. The proposed benefits include improved reproducibility of component alignment, reduced surgical time, and optimised efficiency and cost-effectiveness. Despite these proposed benefits it has yet to be proven to be better than standard techniques[37, 38]. The Australian National joint registry in 2014 estimated this technique was used in 6.8% of all primary total knee procedures. The costs associated with utilizing this this technique are largely absorbed into the cost of the implant. There is a cost to acquire the imaging required to create the PSI as this requires an MRI or CTscan.

Custom Implants

3D printing has allowed the emergence of custom implants [39]. Customized implants for joint arthroplasty are useful when the patient does not fit the standard range of implant size or their disease pattern requires specific implant characteristics in order to achieve correction and function [4]. This has largely been utilised for revision implants in difficult cases (Figure 3). In some instances, revision surgery may not have been possible with traditional implants. DICOM images are utilised to create an anatomical model on a computer. An implant can then be custom designed to fit the anatomical problem. 3D printing has allowed for the manufacture of complex external and internal structures to in an attempt to improve osteointergration and accurately fit the defect site [40].

3D printing is also used in primary implants, for example the manufacture of primary tibial base-plate devices (Stryker -Kalamazoo, MI, USA) [41].

Many of the proposed benefits[42] remain unproven in comparison with traditional techniques at this stage, however there is a paucity of publications at this stage with a lack of long-term follow up in comparison to traditional techniques [43-45].Onerecent article suggests higher manipulation rates following knee replacement surgery with custom implants with no short term benefits[46] however more research is required.

Custom implants can extended to other body parts. Published case reports include custom calcaneus implant with pre-planned soft tissue attachments was created with 3D printing technology for an isolated calcaneus tumour [47](Figure 4).While custom implants are extremely useful in some cases, the technique is not considered the gold standard at this stage and therefore requires careful discussion with each individual patient.

Custom External Fixators and Orthotics

There has been utilisation of 3D printed customised external fixators to assist with fracture reduction [48]. It has been proposed that this technique could incorporate stress adjustment, healing factors and nanotechnology in the future to potentially optimise the fracture healing process.

Many 3D printed braces, splints and orthotics are now available commerciallyhoweverthere is no literature regarding the outcomes and benefits of these braces.

Future Applications

The use and application of 3D technology in orthopaedics is changing rapidly. Its use can be split into two broad categories. The first encompasses industrial applications of the process, resulting in complex models, prostheses, biological scaffoldsand nanotechnology[49]. The second is in every-day clinical use; whereby it can be used for education and surgical planning.

At this stage the industrial uses of 3D printing in orthopaedics is associated with significant costs. The incorporation of this technology into every-day practice will beinfluenced by whether 3D printing techniques can be used to reducecurrent manufacturingcosts,simplify surgery and ultimately improve surgical outcomes.Everyday clinical use of 3D printers for education and surgical planning isbecoming more feasible. The cost of 3D printers has reduced dramatically in recent times with free softwareavailable. Aside from the paucity of clinical trials, the main practical disadvantage is the length of time taken to prepare images and print the model.

Biological tissue 3-D printing has been discussed for some time [50] and animal models demonstrate its feasibility[8, 51][52-54]. This technology is able to print cells or incorporate cells into a 3D scaffold to allow implantation within the body. Examples include regeneration of liver tissue [55], customizable blood vessels [56], skin, bone and cartilage [49] and scaffolds that could include delivery systems for healing factors or nanoparticles [49]. Regulatory barriers limit its widespread clinical use [40, 57] as there are ethical dilemmas with the use of stem cells. Translation ofthe discoveries in the laboratory to human patients still required more high quality trials[58, 59].

Current challenges for 3D cell printing include long-term stability and vascularisation of the engineered tissue[45, 60, 61]. Currentlyno option of printing the cells in the operating room exists as biological printers at this time are large requiring sophisticated computers. These techniques however have the ability to transform the treatment of musculoskeletal conditions that currently have limited options.

3D printed bone scaffolds are being utilisedto optimise the possibility of union particularly wherebone defects exist and atrophic non-unions have occurred. Bone repair scaffolds can be constructed/generated to fit very specific defects [62] whilst growth factors and cell types can be introduced to enhance healing [40, 63-65].

Osteochondral and chondral graft options are also being investigated with multiple osteochondral tissue equivalents being considered in animal models[66, 67] [45]. A sheep model has shown incorporation of 3D printed meniscal grafts [68] (Figure 5).

Conclusion

3D printing applications in orthopaedic surgery are exciting and have the potential to alter future orthopaedic practice.The application of 3D technology in orthopaedics is only recent and hence there is a lack of long term follow up in comparison to traditional techniques. Limitations such as the quality of the model, cost of production and production time are likely to continue to evolve and improve. 3D printing applicationshave the potential to improve surgical outcomes via surgical education, pre-operative planning, custom manufacturing (implants, prosthetics and surgical guides) with future biological applications.

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Figures

Figure 1. 3D model of fractured pelvis to assist with surgical planning and surgery.

"This figure is based on a study first published in Chin Med J, 2015, 128(4): 477-482"

Figure 2. 3D model of planned osteotomy with jig with osteotomy guide.

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Figure 3. Patient Specific 3D printed guides for knee replacement surgery.

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Figure 4. 3D printed calcaneus replacement (Printed with permission from Imanishi, Choong PF [47]).

Figure 5. 3D printed meniscus in a sheep model (Printed with permission from Lee et al.[68])

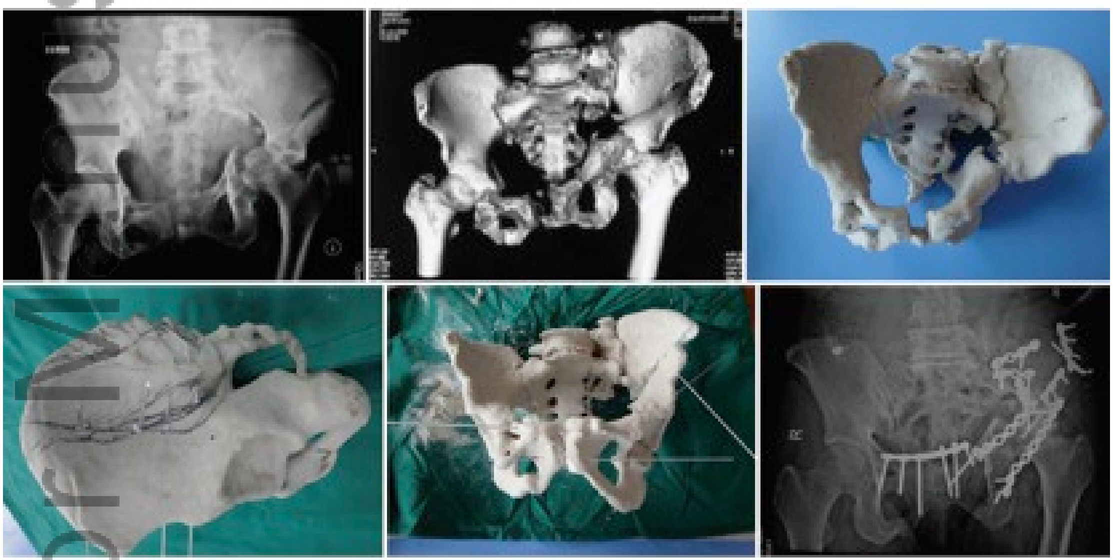

Fig1 Pelvis R1.jpg

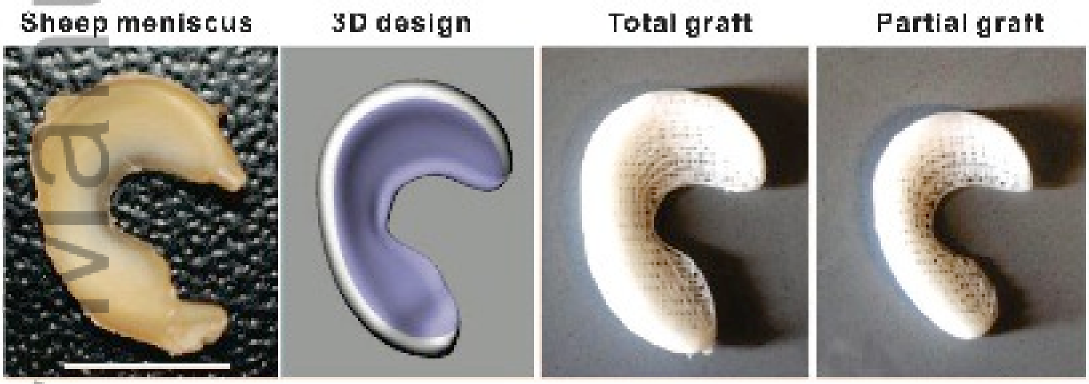

fig 6 Meniscus.jpg

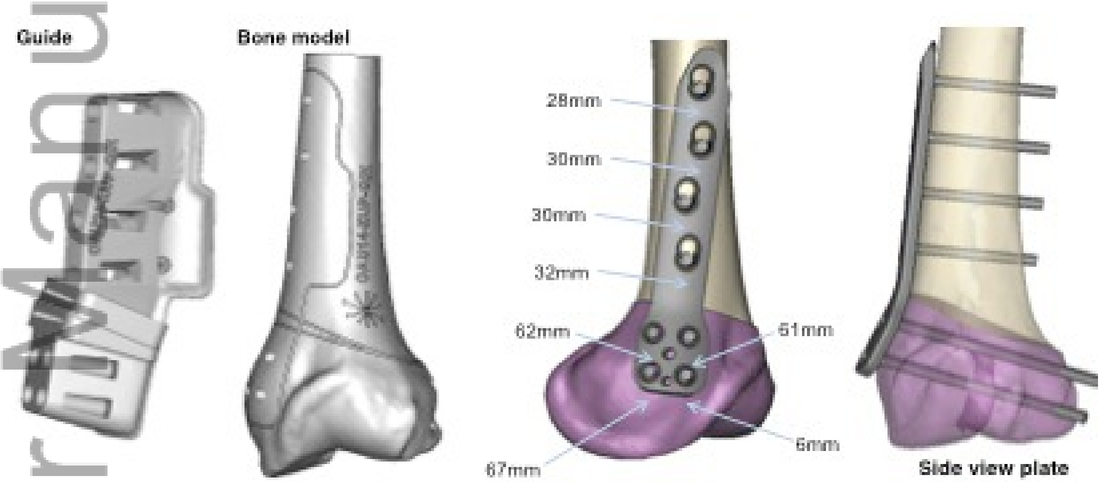

Fig 2 Osteotomy R1.jpg

Fig 3 Custom copy R1.jpg

Fig 5 Calc.jpg