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Role of 3-D printing in foot and ankle surgeries - a comprehensive review

Mr Nagaraj, Prashanth[1] Mr M.Noah Hasan Khan[2], Mr Lokesh Bhambani[3], Mr Devendar paul singh Baghla[4], Dr SM Ajoy[5], Mr Umesh Birole[6]

[1]MBBS, MS(ORTHO), MRCS Ed, FRCS Ed(Tr&Orth). [2]Core surgical trainee, Royal Victoria Hospital Belfast, BT12 6BA. [3,6]Registrar, London Northwest Healthcare NHS Trust

[4]Consultant foot and ankle surgeon London Northwest Healthcare NHS Trust

[5]Assistant professor &Consultant foot and ankle surgeon M.S Ramaiah medical college

***Corresponding Author:**
Mr Nagaraj Prashanth
MBBS, MS(ORTHO), MRCS Ed, FRCS Ed(Tr&Orth)

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Abstract

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INTRODUCTION

The use of 3D printing has changed the process across various industries and enabled the creation of precise customized products. The cornerstone of this concept can be traced back to Charles Hull in 1984 when he filed a patent for the stereolithography fabrication system and eventually began selling 3D printers for commercial use in 1988(Eltorai et al.2015, Jamroz et al. 2018). This technology has improved considerably over the years and is currently being employed in almost every sector. Three-dimensional printing technology has recently gained considerable popularity in medicine but our focus in our study will be the field of orthopaedic surgery. Speaking of trauma and orthopaedic surgery, 3D printing has allowed for the development of anatomical models that help in preoperative planning, education and in the development of patient specific instruments and implants that are be used intraoperatively. This technology is helpful in simple and complex lower extremity cases such as reconstruction of deformities and bony defects, which otherwise can be very challenging. This technology has given surgeons the ability to customize surgical instruments and implants to treat complex deformities frequently seen with foot and ankle pathology. The applications of 3D printing within foot and ankle surgery are endless and as more time and funding goes into research and development of this concept, the clinical utility and benefits will become increasingly evident in times to come.

3D printing and its influence on orthopaedic surgery

3D printing technology is already being utilized within many subspecialties in orthopaedic surgery. A study by Takeyasu et al. (2013) reported 30 patients who underwent correction of cubitus varus deformity with custom made 3D printed surgical guides. Results showed significant improvements in alignment and over 90% of patients reported excellent results. For total knee arthroplasty (TKA) and total hip arthroplasty (THA) cases in patients who have a complex or unique anatomy, 3D printed patient specific instrumentation and implants have become a new treatment option. When comparing to standard implants, patients with custom implants reported to have fewer adverse events such as decreased intraoperative blood loss, and were less likely in the need for post-operative rehabilitation center (Schwarzkopf et al 2015).The technology has indeed given the field of biomechanical engineering new evidence and data to improve on the design and function of the standard implants available. When it comes to THAs, a study by Wan et al. (2019) reported that patients who underwent revision hip arthroplasties with 3D printed acetabular cups had improved stability, better post-operative hip scores, and decreased pain. With all the benefits of this technology to the patient mentioned above, it is prudent to mention that orthopedic trainees have an opportunity to better their surgical skill with realistic 3D patient models and will have a better idea on what to expect intra-operatively. Studies of resident surgeons with regards to the use of 3D models of fractures reported high satisfaction with these models in the planning stage of their operations (Kim et al.2018).

3D printings influence on foot and ankle surgery

Foot and ankle fractures can be difficult to manage given the anatomy and interactions between the several articulations. Anatomical reduction and stable fixation need an appreciation for normal anatomy but also an understanding of the deformity in multiple planes. So far relying on CT and MRI scans to create a 3D image of the deformity has been the main diagnostic tool for surgical planning. However, with the advent of 3D printing technology, there is significant promise of its role in assisting in the preoperative planning of complex cases by providing precise anatomical models. Jastifer et al. (2017) reported on using 3D models in pre-operative planning for deformity correction and fibular lengthening osteotomy. 3D printing has also shown to be promising in foot and ankle trauma. Good and stable fixation of the articular structures around the joint are pivotal for long term mobility. A cohort study done byZhang et al. (2019) compared a cohort of patients who underwent surgical management of high energy ankle fracture dislocations with the assistance of 3D printed models for preoperative planning. with a cohort of similar patients who did not have preoperative 3D models. Results showed that patients who underwent fixation with the models had shorter operative times and less intraoperative fluoroscopy and blood loss. Another study (Yao et al.2019) created 3D models in management of calcaneus fractures to assist with preoperative planning and for implant fixation. Results of the study showed that better precision and accuracy when making bone cuts and osteotomies. Work in subtalar joint arthrodesis and the role of 3D printed custom guides have shown to reduce operative time and radiation exposure from fluoroscopy according to a study (Duan et al.2019).

Osseous defects in foot and ankle surgery often require structural bone grafting. contouring is often difficult to mold to the patient's native anatomy.3D printing has allowed for the development of custom metal implants that provide good mechanical stability while also conforming to the patient's anatomy. Such custom implants can also be designed to accommodate bone growth or space to pack bone graft (Dekker et al.2018). Hlad et al. (2018) studied the use of custom 3D titanium implants in the management of failed foot and ankle surgery. Use of a titanium cage in cases of a failed total ankle arthroplasty and nonunions of a calcaneal osteotomy and a first tarsometatarsal (TMT) joint arthrodesis. The Study reported successful healing at 1-year post-op with no complications. Among all the benefits reported, the ones of particular mention are: better preoperative planning, improved accuracy with bone cuts and osteotomies, and also allows for customized implants in cases of complex deformity and bone loss.

Aims and methodology

Our study aims to highlight the role of 3D printing and its application in foot & ankle surgeries. It will first describe the processing of medical images to formats compatible with 3D printing technologies, before a review of its previous reported use in foot and ankle surgeries. Comprehensive review of literature on role of 3D printer in foot and ankle surgeries was done. Exclusion criterion are Paediatric foot and ankle problems, foot and ankle orthoses and prostheses and isolated fore foot deformities A discussion of the benefits & limitations of its use will follow, with concluding remarks.

3D Printing is when medical images from a CT or MRI scan are turned into tangible physical anatomical models. STL is the basic file format for medical 3D printing software. Central core principle is turning volumetric data into a 3D structure.

First step is to acquire quality data using standard algorithms. Patient-specific modelling (PSM) refers to the integration of patient data with computational models, and this forms the basis of personalised 3D modelling technologies. This is achieved through the high resolving power of multi-detector computed tomography (MDCT) & magnetic resonance imaging (MRI) scanning modalities, which produce highly-detailed images as part of the 'image acquisition' phase. Data is segmented carefully with software and plan and preserve areas that we are interested and turn it to a solid object. 'Image post-processing' entails the processing of these multiple thin-section axial images to generate multi-planar 2D & 3D views. This data is then coded into a form that may be saved to a Stereo-Lithography (STL) file by computer- aided design (CAD) software, through replacement of the contour of a 3D model with a set of polygons, with the number of these correlating with the resolution of the model. This Data segmentation is a crucial part of the process and using dedicated software will produce a more accurate virtual model. Afterwards the data is processed into a series of triangles that will form a structure. The model of triangles is then computed into a pathway, or encoding, for the printer to make the final 3D print. The final '3D printing' phase involves CAD analysis of the STL file, in which the model is "sliced" into super-imposed cross-sectional layers, corresponding to the additive layering of materials by the 3D printer in order to recreate a physical version of the original virtual model. There are various technologies used in this printing stage. Stereo lithography apparatus (SLA) is a liquid-based form, relying on an ultraviolet laser & layers of photosensitive resin. Fused deposition modelling (FDM), on the other hand, is a solid-based form, in which layers are composed of beads of melted thermoplastic which then harden. Selective laser sintering (SLS) and electron-beam melting (EBM) are powder-based forms, using the thermal energy generated by a laser or an electron beam respectively, to fuse plastic or metal powders on the surface of a powder bed. This powder bed is lowered by one layer thickness between the scanning of each cross-sectional image from the STL file & its generation through laser or electron beam fusion of powders at the surface. A new layer of material is deposited on top, and the process continues.

Review of literature.

Rishin J. Kadakia(2020) concluded that 3D printed TTRs represent a specific surgical choice for patients with extreme talar AVN in their study 3D Printed Total Talus Replacement for Avascular Necrosis of the Talus. The pain ratings and patient-reported results of this group of patients improved significantly. In people with talar collapse and AVN, TTR allows for symptomatic change while preserving motion. Twenty-seven patients underwent TTR for talar AVN with a mean follow-up of 22.2 months in this retrospective study conducted over a three-year period.

Francisco Borja Sobron (2019) introduced their series as a surgical tip to locate the plane of resection in shingled Type III and Type IV talocalcaneal coalition using a customised 3D printed surgical guide as pre-op preparation in their article on 3D printing surgical guide for tarsal coalition resection.

In their study 3D Printed Patient-Specific Cutting Guide for Anterior Midfoot Tarsectomy, Louis Dagneaux(2019) found that 3D modelling helped to normalise the miery angle and open up the Djian-Annonier ankle and calcaneal pitch. The osteotomy was divided into three bony slices: a proximal cut at the navicular and cuboid, and two distal cuts at the cuneiforms and cuboid. They expected further bony resection at the first second cuneiform because the top of the deformity at the second cuneiform was linked to more declination of the first ray.

In their systematic analysis on the feasibility of designing, producing, and delivering 3D printed ankle-foot orthoses, Elizabeth Wojciechowski et al(2019) found that the biomechanical effects and mechanical properties of 3D printed AFOs were comparable to those of traditionally manufactured AFOs.. Using 3D printing to create new AFO designs has a lot of potential benefits, such as stiffness and weight optimization to improve biomechanical function and comfort.

In his series on log splitter injury, Yuang Wei Zhang(2019) looked at the Efficacy and Prognosis of 3D Printing Technology in Treatment of High-Energy Trans-Syndesmotic Ankle Fracture Dislocation and came to the conclusion that surgery aided by 3D printing technology to treat log splitter injury is feasible and efficient,, and may be a smart way to come up with a realistic customised surgical plan and improve outcomes.

Glenn B. Pfeffer (2018) used a CT scan of a patient with heel varus to produce 18 similar 3D prints of the talus, calcaneus, and cuboid for their research on Use of 3D Prints to Compare the Efficacy of Three

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Different Calcaneal Osteotomies for the Correction of Heel Varus. To test rotation, coordinate frames were added to the talus and calcaneus. The prints were then divided into three groups, each with six versions. Each osteotomy was precisely and accurately reproduced using a custom jig. Cut models were CT scanned after the simulated operations and compared to six uncut models. He eventually concluded that without the addition of a lateralizing slide or rotation of the posterior tuberosity, Dwyer, oblique, and Z osteotomies did not produce lateral translation or coronal rotation.

Use of Patient-Specific 3D-Printed Titanium Implants for Complex Foot and Ankle Limb Salvage, Deformity Correction, and Arthrodesis Procedures was presented by Travis J. Dekker (2018). Fifteen patients were included in this study who were treated with custom-designed 3D-printed implant cages for extreme bone loss, deformity correction, and/or arthrodesis procedures. Clinical and radiographic follow-up for a minimum of one year was required. In 13 of the 15 patients, radiographic fusion was confirmed by CT scan. All functional outcome score indicators improved significantly, as did pain. He concluded that these patients showed the effective use of patient-specific 3D-printed titanium implants to treat large bony defects, deformities, and arthrodesis procedures in complex large bony defects, deformities, and arthrodesis procedures.

So E, Mandas(2018) concluded that 3D printer technology could play an important role in limb salvage of osseous defects that would otherwise require bone block arthrodesis in their study on the role of 3D printer in Large osseous defects will result during salvage after failed Lapidus bunionectomy, explantation of failed total ankle replacements, and nonunion of Evans calcaneal osteotomy.

Kamran S. Hamid (2016) identified effective limb salvage on a patient with intraarticular distal tibial segmental bone loss, communited talus, and multiple foot fractures in his case study on Salvage of Severe Foot and Ankle Trauma With a 3D Printed Scaffold.

Justin Daigre(2016) in their retrospective, multicenter study included 44 patients who received a total ankle implant (INBONE II Total Ankle System; Wright Medical Technology, Memphis, TN) using PROPHECY patient-specific guides from January 2012 to December 2014 concluded that in the clinical setting, the use of patient-specific instrumentation for complete ankle arthroplasty offered accurate alignment and reproducibility, similar to what was used in cadaveric research. The precision and reproducibility of ankle arthroplasty implantation in a cohort through multiple surgeons were demonstrated in this study using preoperative patient-specific instrumentation.

For complex distal tibial fractures and malleolar avulsion, Kook Jin Chung(2015) documented the benefit of preoperative preparation with 3D printing. They emphasised the need for a patient-sized medial malleolous printed model that could be used as a prototype for contouring hook plates. The benefit of the mini-open technique is that it does not require completely exposing the bone to the contour plate.

Kook Jin Chung (2014) presented a paper on the advantages of using a pre-shaped plate for calcaneal fracture plate osteosyntheses that are less invasive. In this analysis, the non-injured calcaneal side was formatted and printed into a real-size fracture calcaneus model using a CT scan of both calcanei and the mirror imaging technique. However, fractures older than 3 weeks and Sander form 4 may not be amenable to minimally invasive procedures.

AOFAS | October 5, 2018- 3D-Printed Implants Effective in Foot and Ankle Surgery Between 2014 and 2016, researchers from Duke University's Department of Orthopedic Surgery looked at 15 patients who had a custom 3D-printed titanium implant to treat weak bone growth, bone loss, or deformity. Between 2014 and 2016, researchers from Duke University's Department of Orthopaedic Surgery looked at 15 patients who had custom 3D-printed titanium implants to treat low bone density, bone loss, and deformity. Obtaining a computed tomography (CT) scan of the patient and uploading the data to a software programme that enabled 3D manipulation of the bones and joints was the first step in developing the implants in each case. The implant was then engineered and approved by the senior surgeon and company engineers. Unlimited forms, expanded size choices, and fewer morbidity or complications are some of the advantages of 3D-printed implants.

In high-energy trans-syndesmotic ankle fracture-dislocations, studies have shown that 3D-printing technology is superior to traditional surgery in the pre-operative process. The ability to recognise anatomical

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flaws in 3D printed models, such as degree of comminution, articular surface involvement, and bone distribution, aids in deciding whether and to what extent bone grafting is necessary.

Another application of this technology is the 3D printing of customised surgical guides, as demonstrated by Xiao-jun Duan's research in subtalar joint arthrodesis (2019). These will aid in the precise positioning of Kirschner wires, reducing operative times and, more significantly, reducing intra-operative radiation exposure to both the patient and theatre personnel.

Limitations

While this review highlights the importance of 3D printing within foot and ankle surgery, it is important to understand the limitations that come with this new technology. One of the limitations is the cost associated with making the implant. These costs can be a tremendous burden on hospital trusts and patients. There is little evidence to show how much this technology will continue to be used and if costs of production will decrease. An implant will take anywhere from four to six weeks to complete. This time delay has functional reparations to the patient who cannot wait so long for an invasive treatment. Surgeons may have to take extra time to prepare for each case and inspect the instruments and hardware to avoid intraoperative difficulties. The lack of information on post-processing procedures, such as sterilisation, polishing and filling of the lattice structures of implants presents an impediment to its more widespread use in this respect.

Conclusion

The use of 3D printing for the manufacture of titanium implants is a relatively new phenomenon, preventing a vast amount of knowledge to be obtained on the subject. There are unique advantages with this like Potential uses of 3D printing in foot and ankle surgeries include unlimited range of shapes, increased options in implant size, decreased likelihood of morbidity, fewer complications compared to other surgeries, anatomical models for surgical planning and education, customized prosthetics and implants, personalized medical products and equipment, reduced Theatre time, improved patient communication ,preoperative trialing and simulation as well as Improved training and education. There is no doubt that this technology has the ability to revolutionize the manufacturing industry. However, it is hard to predict how much it will be integrated into our daily practice.

Author	Type	Findings
Kadakia et al 2020	Case series	3D printing is becoming more widespread within orthopaedic surgery
Dangneoux &Canovas(2019)	Technique tip	normalising miery angle and open up Djian-Annonier ankle and calcaneal pitch
Wojciechowski et al 2019	Systemic review	biomechanical effects and mechanical properties of 3D printed AFOs were comparable to traditionally manufactured Ankle Foot Orthroesis.
Zhang et al 2019	Retrospective review	Surgery assisted by 3D printing technology to treat log- splitter injury is feasible and effective
Pfeffer et al 2018	Prospective study	With help of 3D printing it was concluded that Dwyer and oblique osteotomies would be best suited for mild deformity,

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Dekker et al 2018	Retrospective case reviews	successful use of patient- specific 3D-printed titanium implants to treat complex large bony defects
So et al 2017	Case series	3d printer in Large osseous defects will result during salvage after failed Lapidus bunionectomy
Hamid 2016	Case report	successful limb salvage with 3D printed scaffold
Chung et al 2015	Technique tip	Advantages of pre operative planning with 3D printing for complex distal tibial fractures

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