Application of 3D printing in orthopaedic surgery. A new affordable horizon for cost-conscious care

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Abstract

Application of three-dimensional (3D) printing facilities in orthopaedic surgery is getting popular in resource-constrained countries. It is cost- and resource-efficient to assist in planning and increasing orthopaedic procedures efficiency. Furthermore, it improves educational training and provides cheaper prosthesis and creation of customised implants for special cases. Moreover, 3D models of computed tomography (CT) and magnetic resonance imaging (MRI) data play a helpful rule for a more hands-on approach for the surgeon. Like evidence-based medicine practice, researchers are exploring new areas of patient-specific instrumentation in the surgical field, searching for favourable and cost-effective results. Three-dimensional printing has shown promising results for quick and cost-effective solutions in several fields. Many fields of application are dependent on various uses of 3D printing, but it has yet to be used widely in medicine and orthopaedics. The current literature review was planned to highlight the advantages of using 3D printing, its scope in surgical field with emphasis on orthopaedic surgery, and the limitations of its use in developing countries.

Keywords: Three dimention; printing; orthopedic; orthopaedic; surgery

What is 3D printing?

Three-dimensional (3D) printing, also recognised by different names like "rapid prototyping", "solid free-form technology" or "additive manufacturing", is a phenomenon in which models or objects are created by fusing or grouping material in layer with the help of computer software. It does not require any model. A variety of materials available are used in this process, including plastics, metals and ceramics. In recent years, advancement in technology has decreased the price of 3D printers to such an extent that its uses have expanded in surgical training, patient education, research and publication.[1] It is used for the formation of cranial prosthesis in various cases of cranio-maxillo-facial[2] and jaw defects, to reconstruct earlobes, tracheas[3] and dermal skin grafts. Modern technology in 3D printing has revolutionised preoperative planning, custom-made implants and instrument production.[2,4] Examples include the 3D Rendition of Cardiovascular Anatomy for Surgeons to form a strategy to tackle the case when conventional data is unable to help plot a fast and efficient surgical plan. Sometimes a special/customised instrument is needed to tackle cases where normal instrumentation is unable to perform efficiently, and these instruments can be quickly fabricated and put to use. In 1984, Hall was the first person who introduced this technology by developing stereolithography.[5]

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Generation of 3D objects

In case of patient-specific analysis, correct medical imagining data should be collected which gives individual patient an identity. For this purpose, computed tomography (CT) and magnetic resonance imaging (MRI) are available for provision of high-resolution 3D image data. Various tools are available to create multiplanar reformatted 2D images and 3D views of patient's own anatomy. The technique of converting medical image into 3D object consists of three processes that include image acquisition, image post-processing, and 3D printing.[6]

Image acquisition

This is the first step in 3D printing. As resolution of 3D models produced from medical images depends on the images themselves, so high-quality medical images should be collected. In the medical field, these images can be obtained from CT and MRI. In orthopaedics, CT is the imaging modality of choice when studying bones. Multidetector CT (MDCT) produces a slice of axial image with less than 1mm thickness and isotropic voxel.[7] In MRI, there is no risk of radiation exposure during the imaging process. It is far superior in delineating anatomy of soft tissues; for instance, damage to articular cartilage, extension of tumour and involvement of neurovascular bundle.[8]

Other modalities are also used for data collection, like positron emission tomography (PET), single photon emission computed tomography (SPECT), cone beam computed tomography (CBCT) and ultrasonography (US). These are non-invasive imaging modalities. Whatever imaging modality is used for data acquisition, data is saved in the common digital imaging and communication in medicine (DICOM) format.[6]

Imaging post-processing

Various post-processing tools are used for processing the DICOM images. These softwares collect images to create 2D images by means of multiplanar reformation. Coronal and sagittal images are used for better clinical interpretation. For example, pelvic fractures and joint alignment may not be apparent on axial images. For segmentation of regions, a technique of thresholding voxel intensity value is employed. Three-dimensional objects can be extracted from the segmented region of interest. Computer-aided design (CAD) software transforms the contour of a 3D model into polygons, commonly triangles, the number of which directly correlates with resolution.[9] Data from CAD is converted into 3D file format; stereolithography (STL). After editing of STL files, CAD data is processed through printing machine into object fabrication.

3D printing

STL files are analysed by CAD software to produce 3D model. Three-dimensional printing is a process using 3D CAD data for creating 3D physical models. It is sometimes referred to as rapid prototyping; computer-automated or layered manufacturing depending on production method used for processing. In 3D printing, 3D computer models are used to reconstruct 3D physical model by adding material layers.[10] In additive fabrication, the machine lays down layers of powder, liquid or the sheet material and in this manner model is created from a series of cross-sections. These layers are then manipulated to produce a model. Some fabrication processes employ two materials in the course of creating parts. The first material is the base material and the second is the support material. The support material is later removed by heating, or dissolved with a solvent or water. Due to advancement in fabrication techniques, it is now possible to produce a model by adding materials of different elasticity or colour. Hence, realistic models are produced which are now attractive to educational or research purposes or to produce naturally-looking prosthesis. On the basis of manufacturing process, 3D printing technology is classified which commonly includes stereolithography apparatus (SLA) , fused deposition modelling (FDM), selective laser sintering (SLS) or electron beam melting (EBM).[11] STL requires photopolymer which can be cured by ultraviolet (UV) laser. Selective laser sintering (SLS) is dependent on tiny particles of thermoplastic metal, ceramic or glass powders that are joined by laser. Various materials include polymers (nylon, glass-filled nylon or polystyrene) and metals (steel, stainless steel alloys, bronze alloys or titanium). FDM is based on extruding small beads of thermoplastic material. Laminated object manufacturing (LOM) introduces layers of paper or plastic films that are pasted together and shaped by a laser cutter. Inkjet printers use fine powders such as plaster or starch.

Orthopaedic application of 3D printing

3D printing is new in healthcare system compared to other industries. During the last decade, tremendous development occurred in this technology with wide use in patient care, research and education system. However, it has limited application in the orthopaedic field. Few case reports or series are available describing anatomic model for surgical planning, prosthesis and fabrication of customised implants.

Surgical planning

In the past, orthopaedic surgeons usually used 2D plain X-rays and CT images for bony anatomy. They found difficulty in making proper templates for complex fracture of pelvis and acetabulum. Reconstruction options were limited due to lack of variety of customised prosthesis. Time of surgery was more with greater loss of blood, resulting in enhanced morbidity and even mortality. Literature has proved that short operative time reduces blood loss and decreases anaesthesia time, resulting in speedy recovery of patient and thereby reducing complications.[12] With advancement in imaging modalities, 3D images are employed with great success. Now modern technology has enabled surgeons to study on-patient specific physical bone models which are created using the patient's own CT image data by 3D printing. Introduction of 3D printing technology in orthopaedic surgery is a new innovation in terms of management of either orthopaedic trauma or deformity correction.[13] The most important benefit of these models is that they enable surgeons to familiarise themselves with tactile and visual understanding of patient-specific anatomy and pathology.[14] It also aids in proper planning of difficult orthopaedic procedures like a case of correction of mal-alignment or oncology-related pelvic orthopaedic reconstruction.[15] Its application in preoperative planning of periacetabular osteotomies in hip dysplasia and predicting results of corrective surgery in scoliosis has been well documented in literature.[4,14,16] Besides, 3D images can help to accurately classify complex acetabular fractures.[17] Plate contouring can be done easily on models. These pre-contoured plates help in fracture reduction and ultimately fixing fracture.[18] A prospective study was conducted on surgeon's perceptions of 3D printed models to assist with complex surgical cases in paediatric spine and pelvis with anomalies, significant improvement was noted in designing a surgical plan, selecting important type of external fixator, intra-operative reference of patient's anatomy, precision, osteotomies and communication with patients.[19] Because of proper planning with 3D printed models, surgical time was reduced in patients with congenital spinal deformities. These models can be sterilised so that the surgeon can manipulate models on the operative field, thereby aiding in delineation of correct anatomy and accurate resection in bone tumour surgery. Bizzotto et al demonstrated in a study that preoperative analysis of 3D printed models of patient bone fracture compared with analysis of 2D and 3D reconstruction on screen alone showed better understanding of fracture patterns with 3D models representing correct joint fragmentations and articular surface pattern, thereby helping in reduction and fixation.[20] Hence, application of 3D technology has revolutionised operative management in orthopaedics with greater ease.[12]

Medical education and training

Accurate knowledge of human anatomy and topographical relations of various anatomical structures are essential parts of medical education and of performing surgical procedures. The 3D models can be utilised for education and preoperative discussions about various surgical options. In different paediatric orthopaedic disorders, like Perthe's disease, Blount disease, physeal bar and coalitions,[21] the use of 3D models has been reported with promising results.[21] These models are effective in describing anatomy and musculoskeletal pathology by the surgeon and the therapist to the patient. It also aids in consent process for patients with complex acetabular fractures, thereby increasing patient and family satisfaction.[14] These models are preserved for educational purposes of surgeons, medical students and physicians. Rapid prototyping models help in the provision of intensive training for newer surgeons, for instance, handling in vivo conditions, while endovascular stent implantation can be done without the risk of patient complication.[22] By getting adequate training, surgeons feel confident about their skills when performing surgery.

Implants

The 3D printing technology has its own role in medical prosthesis and designing processes. To repair various bone structures, custom-made 3D printed implants are available. These are widely used in femur,[23] pelvis and tibial hemiarthoplasty.[24] A bilateral total hip was performed with the help of 3D printed implants at Mayo clinic in a dwarfism patient too small for conventional implants.[25] The surgeon printed her hip model and custom-made implant according to the model was manufactured which was later used for joint replacement. Similarly, a 3D printed titanium implant was used to replace cancerous cervical vertebrae in a patient.[26] Various advantages of this technique are reported in literature, including the production of implant of the same size and geometry as of the original bone which decreases pressure on surrounding tissues in comparison to conventional implant. In addition to this, implants with osteo-conductive pores can be manufactured to enhance natural bone growth.[18] Biocompatible materials like metals, ceramics and polymers are commonly employed. Hydroxyapatite-coated total hip implants are preferred material for reconstruction.[27] Polycaprolactone is a biodegradable polymer used for bone and cartilage healing.[10] Production of cellular tissue scaffolds for cellular growth has also been described in literature.[28,29] Advancement in future predicts development of artificial organ according to individual patient's anatomy and needs. More researches are essential in order to produce viable tissue and their implication on patients without risks of life.

Casts

There are lots of problems associated with conventional plaster casts such as restricted access to enclosed area, lack of breathability, increased height and the need to maintain dryness of the cast. However, 3D printing has solved all these problems with the production of a new cast known as "cortex". The cortex produces a hardened mesh to cover the site of injury. Inconvenience in the provision of this cast can only be dealt with by making sure that 3D technology is easily accessible to surgeons and radiologists. It should be made sure that lightweight casts are readily available to adequately immobilise the fracture.[30]

Limitations

Although 3D printing is serving humanity in different ways, it has also brought forth ample limitations. The most important could be restriction of the size of imaging data. We cannot produce whole body models. This can be controlled by dividing image into small pieces which are combined after printing. Time is required for producing a model, while availability of manufacturing implant and its cost are also hindrances in the creation of 3D printing designs. Finally, experts are needed to run the whole chain of 3D printing process. With the advancement of technology, cost of doing business and machineries is dropping which is encouraging the use of the printing process.

The present and the future

In recent years, rapid progress has been observed in 3D printing technology with its expanding application in the field of medicine. It works in a chain requiring a multi-disciplinary approach starting from collection of imaging data, image post-processing and manufacturing of 3D model by different techniques. Key is the involvement of a radiologist who connects engineering to medicine. Other team members include clinicians, computer and material experts. Application of this technique is increasingly expanding in various fields of healthcare system, beginning with diagnosis, counselling of patient and family, treatment planning and intra-operative navigation.[31] By simulating surgical procedures, it is playing an important role in the training of surgeons and medical students.[32] Additionally, it has promising results in the development of customised implants and prosthesis.[33,34]

Scientific research is a key feature for future development and progress of medicine. Rapid prototyping has proved beneficial results in serving the mankind by opening a new window for future progress in the field of physiological and pathological processes. Now scientists are looking forward to the creation of artificial organ and tissues, but its use is limited.[35]

Conclusion

Three-dimensional printing is proven to be an emerging art and a new innovation with a variety of different medical applications, especially in orthopaedics, for instance, in patient care, biomedical research and medical education system through creation of anatomic model for surgical planning, prosthesis and fabrication of custom-made implants. Because of its certain limitations, it is not being clinically practised as a matter of routine. However, in the near future, due to advancement in technology, it will be available to the general public. It will be opening up a new market which is revolutionising modern technique of medical practice for every healthcare provider and seeker.

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