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Review article

Additive manufacturing applications in orthopaedics: A review

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ABSTRACT

The applications of Additive Manufacturing (AM) have increased extensively in the area of orthopaedics. The AM applications are for making anatomic models, surgical instruments & tool design, splints, implants and prosthesis. A brief review of various research articles shows that patient-specific orthopaedic procedures provide multiple applications areas and provide directions for future developments. The purpose of this paper is to identify the best possible usage of additive manufacturing applications in orthopaedics field. It also presents the steps used to prepare a 3D printed model by using this technology and details applications in the field of orthopaedics. AM gives a flexible solution in orthopaedics area, where customised implants can be formed as per the required shape and size and can help substitution with customised products. A 3D model created by this technology gain an accurate perception of patient's anatomy which is used to perform mock surgeries and is helpful for highly complex surgical pathologies. It makes surgeon's job accessible and increases the success rate of the operation. AM provides a perfect fit implant for the specific patient by unlimited geometric freedom. Various scanning technologies capture the status of bone defects, and printing of the model is done with the help of this technology. It gives an exact generation of a physical model which is also helpful for medical education, surgical planning and training. This technology can help to solve present-day challenges as data of every patient is different from another.

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1. Introduction

In recent years, there has been a significant improvement in additive manufacturing technologies, and researchers have explored its applications in various fields of engineering and medicine. It creates a physical model from the digital 3D model without any requirement of process planning, physical tools and dies. This technology has great capability to fabricate complex shape prototypes with a variety of materials such as nylon, polymers and even metals. It produces implants of biocompatible materials that meet structural requirements.[1,2]

Additive manufacturing is a type of manufacturing technology in which materials like powder, plastic or metal are deposited layer by layer to fabricate the 3D model from Computer Aided Design (CAD) model. This method is different from traditional manufacturing technology because rather than removing of material; it adds materials layer by layer. In surgical applications, this technology is used to create a model which gives a better understanding of complex pathology and anatomy of the patient. It easily produces specific custom implants and patient-specific instruments which help surgeon during the surgery of the patient.[3,4]

In biomedical engineering, orthopaedics is surgical discipline applied through various disciplines such as joint arthroplasty, ranging from trauma surgery to tumour surgery for correction of the deformity. Orthopaedic applications provide a detailed analysis of the musculoskeletal system and craniomaxillofacial surgery.[5,1]

Applications of additive manufacturing give a flexible solution with quick and cost-effective production of implants and also surgical instruments with high-quality of patient-specific. AM offers multiple benefits as compared to conventional implant production methods. By 3D CAD data, patient-specific parts are produced without using any tool along with required medically compatible materials and with a high quality of accuracy and precision. It makes surgeon job easier and optimise patient's treatment with minimum unpleasant side effects. AM methods can produce individual instrument and easily manufacture various medical devices. This technology is recasting in orthopaedic care that rapidly fabricates implantable devices by the use of bioactive materials and polymer.[6,2]

In orthopaedics, AM has extensive benefit for bone ingrowths capabilities. It enables to fabricate complex metal parts of the

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different shape, size and design. Regarding improving lives, it has a dramatic effect on the human condition. This is helpful for both clinical environment and manufacturing method. It creates implant of spinal devices, standard knee and helpful in the development of orthopaedic implant.[6,7]

2. Generation of 3D objects by using additive manufacturing applications in orthopaedics

In orthopaedic the patient-specific analysis is essential to obtain an accurate medical imaging data of the individual patient. Magnetic resonance imaging (MRI), modern multi-row detector Computer Tomography (MDCT), Computer tomography (CT) scan, X-rays and 3D scanners provide an accurate, fast, high-resolution data and easily prepare a 3D view of patient's anatomy. AM convert the digital medical image into a 3D physical model. This conversion takes place in three steps discussed in Table 1.

The data is captured by advanced medical imaging, making the diagnosis reliable and more manageable.[14,15] 3-D reconstruction images from these scanning technologies provide superior visualisation. This provides better surgical management and accurate diagnosis. These scanning technologies give 3D pictures displayed on a computer screen which cannot affect the perception of a physical model for complicated cases. For this, it is necessary to print these 3D models by the additive manufacturing technologies for the complete understanding. These 3D printed models provide better information to the surgeon. Before printing it is necessary to prepare DICOM which is extracted from the medical imaging and then convert it into STL format to complete the printing process by 3D printing machines.[1]

3. Applications of additive manufacturing in orthopaedics

Additive manufacturing provides tremendous development in manufacturing field and now explore its applications in various medical fields. The 3D printed model's first goal is to resemble the cases in the clinic and give a detailed overview to the surgeon. The principal application of this model is for the testing procedure in advance as it provides a feeling of the mechanical response of real bone to the surgeon. The operation can also be performed on the 3D model to examine and visualise before performing actual surgery. Table 2 describes various applications of additive manufacturing in orthopaedics.

The applications of additive manufacturing in orthopaedic surgery provide reproducible, safe and reliable models that improve patient outcomes and reduced operating time as compared to traditional surgical techniques. This technology can work successfully for preoperative planning, education and custom manufacturing. For Custom manufacturing applications it is used for prosthetics, surgical guides and implants. 3D printed models of anatomy have assisted in the education of students, trainees, patients and surgeons. Surgeon and doctors can use 3D printed bone model for practising of surgery and explain the patient or students about the surgery. It also has potential to increase the number of tools for the surgeon and easily undertake the redesigning. It becomes a valuable tool that has an impact on every area of medicine. Surgeons can now develop new tools and techniques for surgical procedures.

4. Discussion

Additive manufacturing easily develops personalised prostheses and implants which is more valuable in the field of orthopaedics. This technology can rapidly fabricate implants of any desired shape and also used for the production of size-controllable micro-pore structures. For research and development of orthopaedic implants, it is promising. Its applications are enhanced in medical and solve various problems regarding this field. 3D printed physical model can help surgeons to have a visual and tactile understanding of the patient-specific pathology and anatomy. Surgeon and patient can now understand easily about the medical conditions with a real 3D physical model. It increases the patient satisfaction and safety. It is helpful to give training to the doctor and medical students for better understanding of the various types of fractures. Customised and high-quality implants with a wide variety of material are quickly built to meet the required standard in orthopaedics with minimum risk. By changing the properties of the raw material, this technology tends to reduce the weight of the implant. It gives a flexible solution with the quick and cost-effective production of various medical tools and devices.

5. Limitations and future scope

The cost of additive manufacturing technology is very high that includes software, hardware, skilled human resources for

Table 1
Generation of 3D objects by using additive manufacturing applications.

S No	Steps used	Description	References
1	Image acquisition	• High-quality medical image with high resolution in 3D virtual form is generated from various scanning technologies • Image acquisition is the most critical step because physical model accuracy depends on this • CT, MRI and 3D scanners are mainly used to capture the image for this purpose	Wong[6]; Souzaki et al[8]; Verma et al[9]; Lal et al[10]
2	Image post-processing	• DICOM (Digital Imaging and Communications in Medicine) images are extracted for data reconstruction by the use of image post-processing software • It is useful for examining skeletal structures and detailed information about joint alignment and fractures • CAD software transforms the 3D model into a series of polygons and converts data into standard triangulate language (STL) format • The input to the 3D printing machine for part fabrication, the data file is in STL format • DICOM images also play an important role in medical imaging data for the specific patient and 3D printing technology	Jardini et al[11]; Trace et al[12]
3	3D printing	• CAD software divides the 3D model into "very thin" cross-sectional layers • Additive manufacturing technologies fabricate 3D physical model by adding material layer by layer	Javaid and Haleem[1]; Martelli et al[13]

Table 2
Applications of Additive Manufacturing in Orthopaedics.

S No	Applications	Description	References
1	Anatomic models for the planning of surgery	• Traditionally the preoperative planning by an orthopaedic surgeon is done with the help of 2D Plain CT images and X-ray to assess the pathology and bony anatomy of the patient • By the application of AM advanced image post-processing software is used to produce 3D images and 3D non-axial reformatted images • The 3D anatomy can be viewed, and patient-specific physical bone models can be regenerated from patient's 3D data by using additive manufacturing technologies • This physical model can help surgeons to have a visual and tactile understanding of the patient-specific pathology and anatomy	Pacione et al[16]; Vaish and Vaish[17]; Pietrabissa et al[18]; Souzaki et al[8]
2	Cost-effectiveness for orthopaedics	• Traditionally there are standardised instruments that are not useful for every patient • AM produced higher productivity customised implants and instruments at a lower cost as compared to the conventionally manufactured system • The surgeon can easily achieve high-quality product to meet the required standard in orthopaedics • It is a cost-effective tool for the hospital which fulfils the customised requirement of the surgeon	Trace et al[12]; Salmi et al[19]; Javaid et al[20]; Kumar et al[4]
3	Surgical guides	• AM is applied successfully for the fabrication of patient-specific surgical guides and implants • It is used for a tumour, total joint arthroplasty and deformity correction • It helps surgeons for the designing of surgical cutting guides which perfectly match the anatomy of the patient with reasonable accuracy • For synthetic devices and individually printed implants, this technology is used efficiently for even complicated cases such as a spinal tumour and pelvic tumour • By the applications of this technology, surgical tools can also be redesigned and manufactured	Yap et al[21]; Wong et al[22]; Javaid and Haleem[1]
4	Patient-specific instruments	• Patient-specific instruments are made by the bony anatomy of the 3D surface model • It is created from image segmentation of a patient which is easily fabricated by AM technologies for orthopaedic applications • Used for easy replication of surgical plans which involve for drill in a specific planned direction and guiding a saw • Helps for performing difficult osteotomies and guide accurate implant placement of the knee • For oncological clearance, this technology helps to improve the bone resection accuracy and aids in bone tumour surgery	Trace et al[12]; Negi et al[2]; Han et al[23]
5	Bone tissue engineering	• It is an interdisciplinary field which combines biomaterials, cell and biochemical factors to regenerate a new bone • Currently, structurally sophisticated bioscaffolds production is done by AM technology • To achieve mechanical and biological properties 3-D bioscaffolds is designed as per the requirement of the clinical application	Zein et al[24]; Peltola et al[25]
6	3D-printed custom implants	• Traditional manufacturing methods are used to fabricate standard-sized bone implants and fulfil the surgical requirement for most of the patients, but they do not accurately fit, and there is a level of discomfort and poor functionality • AM technology create a 3D bone implant from patient's medical image with perfect match that fulfils the requirement • Improves the surgical results which give perfect fit of patient anatomical and medical implant requirement	Jardini et al[11]; Wong et al[7]
7	Bone Defect	• 3D scanning technologies are easily used to capture bone defects which are converted into 3D virtual model form and import to additive manufacturing technologies for build 3D physical model • From this model, the surgeon can easily see the status of defect or damaged bone • Help surgeon to complete surgery precisely and successfully	Han et al[23]; Pietrabissa et al[18]
8	Improved patient care	• For specific patient AM produced an implant more precisely that reduces the risk of the operation • The operation can perform with a minimal invasion that lessens the overall stress of the patient	Salmi et al[19]; Boonen et al[26]
9	Precision for surgeons	• The operation performed by various surgical instruments manufactured by additive manufacturing technologies is easier for the surgeon • The design can be optimised, and its functionality can be enhanced	Yap et al[21]; Choi and Kim[3]
10	Weight reduction of implants	• Manufacture implants which have less weight • This technology has exceptional tendency to reduce the weight of the implant by changing properties of the raw material • Due to freedom of design, it produces complex geometry implant with optimum weight • By reduction in weight of implant, the patient feels comfortable	Wang et al[27]; Peltola et al[25]
11	Osteochondral and Chondral defect	• AM is helpful for Osteochondral and Chondral defects • The volume of these defects is also examined through the applications of this technology and helps to solve the problem of these type of defects during operation	Boonen et al[26]; Pacione et al[16]

Table 2 (*Continued*)

S No	Applications	Description	References
12	Education and surgical training	• 3D-printed patient-specific models can be used for preoperative discussions and education about strategies • The application of the 3D printed model has been used for Blount disease, Perthe's disease, physical bars or coalitions • It also assists therapists, surgeons, and patients for a better the understanding of patient's musculoskeletal pathology • Families of the patient can understand better about medical conditions of a patient with real physical models printed by additive manufacturing technologies • Increase the patient satisfaction and safety • 3D model can be used to train doctor and medical students for better understanding of the various types of fractures • Helps the surgeon to practice on prototype printed by this technique and more familiar with patient-specific scenarios	Mahmoud et al[28]; Sodian et al[29]; Hurson et al[30]

operating, maintaining as well as the cost of printing materials. AM creates implants with high cost and also required a high cost of designing. Another limitation of this technology is the timescale physical model production. It is variable that depends on the complexity and size of the model. Image acquisition and data processing take time. Then for the fabrication of model, it depends on the types of technologies of additive manufacturing. The machines take 24 h to complete the printing process of the standard model. Model printed by this technology has limited application. In some cases, it is not implemented and can only be used for a better understanding of the actual surgery. In orthopaedics, implants printed by AM technology are fabricated layer by layer and bonded together. Sometimes mechanical strength that the user required is not achieved and thus makes it unsuitable for long-term use.

In future, 3D-printed custom implants can be a suitable adjunct for the patients. Artificial bone consist mechanical properties that are similar to human bone. It opens a reconstruction option that helps orthopaedic surgeons, radiologists, and implant companies. By using this technology surgeon take help to facilitate customised patient treatments of their patients. It presents new opportunities in orthopaedics for exact generation of the physical model which is also suitable for education, surgical planning and training. This technology can solve present-day challenges in medical because, in medical, the data of every patient is different from each other. Among different care providers, it provides seamless communications. This can give elastic properties and strength close to the actual bone. It produced the implant of required shape and size before the actual surgery that improves quality of surgery of the patient. It helps to impart an enhanced long-term quality of life of the patient.

6. Conclusion

Additive manufacturing is a type of manufacturing process that produces a 3D object from the digital model. Based on CT and MRI, the bone 3D image can be reconstructed, and then obtains a bone prototype by layer by layer technique and play an effective role in medical as well as in orthopaedic surgery. This is helpful for surgical design, teaching and presentation of complex surgeries. By using reverse engineering technique of AM, a missing part of the bone is created. The popularity and advancement of this technology are for implant design and fabrication, tissue engineering, preoperative surgical planning and even in training of doctors and surgeon. It produces an implant of the individual patient at a fast pace which fits better as compared to standard implant manufacturing by the traditional manufacturing process. The true physical model produced by this technology allows the surgeon to have a better understanding. Production of scaffolds for bone tissue engineering is another application of this technology which is used for the fabrication of structurally sophisticated bio-scaffolds. 3-D bio-scaffolds are designed as per the need of clinical applications with significant mechanical and biological properties. 3D printed surgical guides simplify the surgery that reduces operative time and makes surgery precise. CT and MRI scan are used to capture data, and additive manufacturing technologies are used to make surgery successful.

Conflict of interest

None.

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