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Review

The role of additive manufacturing for biomedical applications: A critical review

Rakesh Kumar [a,b,*], Manoj Kumar [c], Jasgurpreet Singh Chohan [c]

[a] Ph.D. Research Scholar, Department of Mechanical Engineering, Chandigarh University, Gharuan, Mohali, India
[b] Department of Mechanical Engineering, Chandigarh Group of Colleges Landran, Mohali, Punjab, India
[c] Department of Mechanical Engineering, Chandigarh University, Gharuan, Mohali, India

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ABSTRACT

Additive manufacturing (AM) is a digital manufacturing technology, rapidly revolutionizing in the medical sectors for printing of distinct body parts having intrinsic shapes and offering customized solutions to every patient. In the past few decades, AM is used as a versatile and cost-effective method for the manufacturing of geometrically complicated shape in the medical industry. In addition, AM technology is used for the development of products from dental implants to heart valves and joint replacements etc. This is the technology that makes a physical model directly from CAD models by adding materials in layer by layer fashion and offers robust mechanical properties. This review paper aims to consolidate the contribution of various researchers in the area of AM especially focusing the applications in the medical field using various technologies of AM, materials and their mechanical properties, so that this review paper could become the torch bearer for the futuristic researchers working in this area.

1. Introduction

Additive manufacturing is an advanced technique used for the manufacturing of complex geometries and structure by adding material in layer form, using 3D model data [1]. Additive manufacturing is also known as rapid prototyping, or on-demand manufacturing, or digital fabrication, or desktop manufacturing, or solid freeform manufacturing, or layer manufacturing, or direct manufacturing technique, or 3D printing [1,2]. There are distinct additive manufacturing techniques such as: Stereo lithography (SLA), Digital Light Processing (DLP), Selective Laser Sintering (SLS), Electron Beam Melting (EBM), Fusion Deposition Modeling (FDM), Multijet/Polyjet 3D printing, Selective Laser Melting (SLM) and Laminated Object Manufacturing (LOM) etc. These techniques uses distinct materials such as ceramics, plastic, metal, liquid, powder or even living cells [3]. These technologies can fabricate any complex 3D component of any shape by utilizing 3D model data, which is impossible to fabricate by traditional manufacturing techniques. In a basic setup, the 3D model data is converted into standard triangulate language format, which is simple to print by additive manufacturing technique as shown in Fig. 1.

All these processes utilize the similar basic principle where the final desired part is fabricated with the deposition of the materials layer by layer [4–6]. Although, in medical sector, the 2D radiographic images such as computerized tomography, magnetic resonance images and X-rays can be converted to three dimensional digital print files, allowing the creation of customized anatomical, complicated and medical structures [7]. Recently, additive manufacturing has a great potential in medical sector and are expected to revolutionize health care. The most widely used biomedical applications of additive manufacturing includes fabrication of tissue and organ; anatomical models, development of customized prosthetics and implants, development in pharmaceutical field especially in drug dosage forms, discovery and delivery etc. [8,9]. The extensive use on additive manufacturing in medical field is due to many merits such as customization and personalization of medical products, biocompatibility, cost effectiveness, improved productivity, accessibility, short production time, simple assembly and collaboration and democratization [10–15]. Although, additive manufacturing is still not extensively used in mass production owing to low speed [16–21]. But, this limitation is considered as a merit in medical sector where high precision and customized product is required in less quantity. This is due to the fact that requirement of medicine and customized therapy changing from one patient to another. Hence, additive manufacturing is well suitable and most widely used in clinical and biomedical applications [22–27]. Many researchers and scientists had attempted to map

* Corresponding author at: Department of Mechanical Engineering, Chandigarh University, Gharuan, Mohali, India.
E-mail address: rk05691@gmail.com (R. Kumar).

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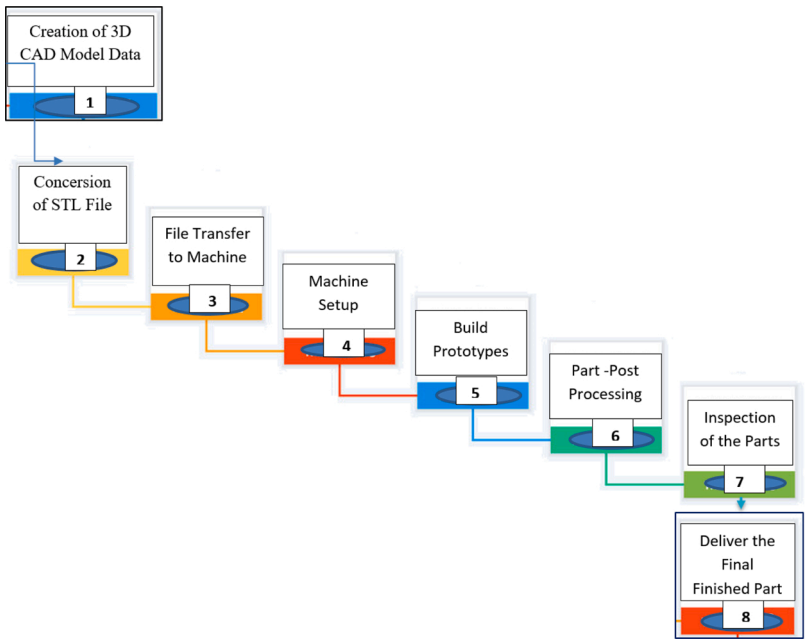

Fig. 1. General Steps involves in 3D printing [1].

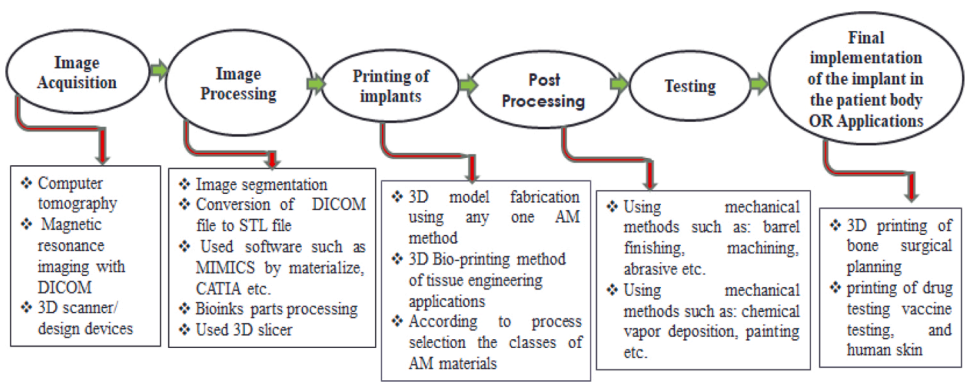

Fig. 2. Steps involves to fabricate 3D medical models.

human organs, convert them into three dimensional virtual designs and presently investigating to search bio-comparable material to produce vascularized human.

However, some regulatory and scientific challenges are still remain [10,28]. The distinct steps required to fabricate the 3D medical models include image acquisition i.e. choosing the structural target area, the evolution of the three dimensional geometry by processing of the medical images, selection of materials and three dimensional machine for implant printing, post processing if required, testing and final application or implementation in implant body as shown in Fig. 2.

Medical model help to enhance the knowledge and skill of surgen such as better understanding of diseases, cost, surgical process, application of surgical tools and patient-specific design of implantable devices etc.[29–33]. Medical additive manufacturing is best suited for custom fit mask, new organ development and operation practice etc. [34]. This review article is mainly focus on distinct 3D printing applications in medical sector, future scope along with merits and demerits.

2. Historical development of additive manufacturing in medical sector

The historical technological developments of AM and its future prospects indicates that 3D printing techniques have come a long way

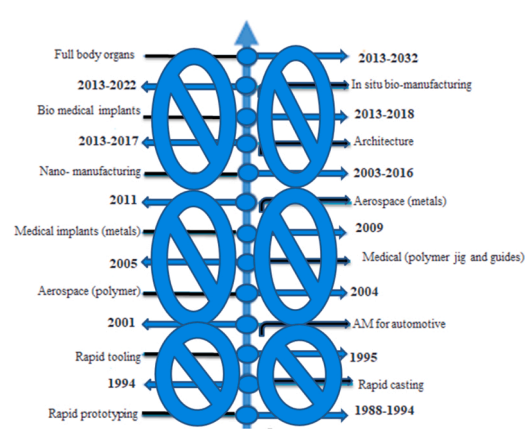

Fig. 3. Timeline of the scientific and technological developments of additive manufacturing, indicating past, present and future potential. Source: Courtesy of Graham Tromans); Aranca Analysis.

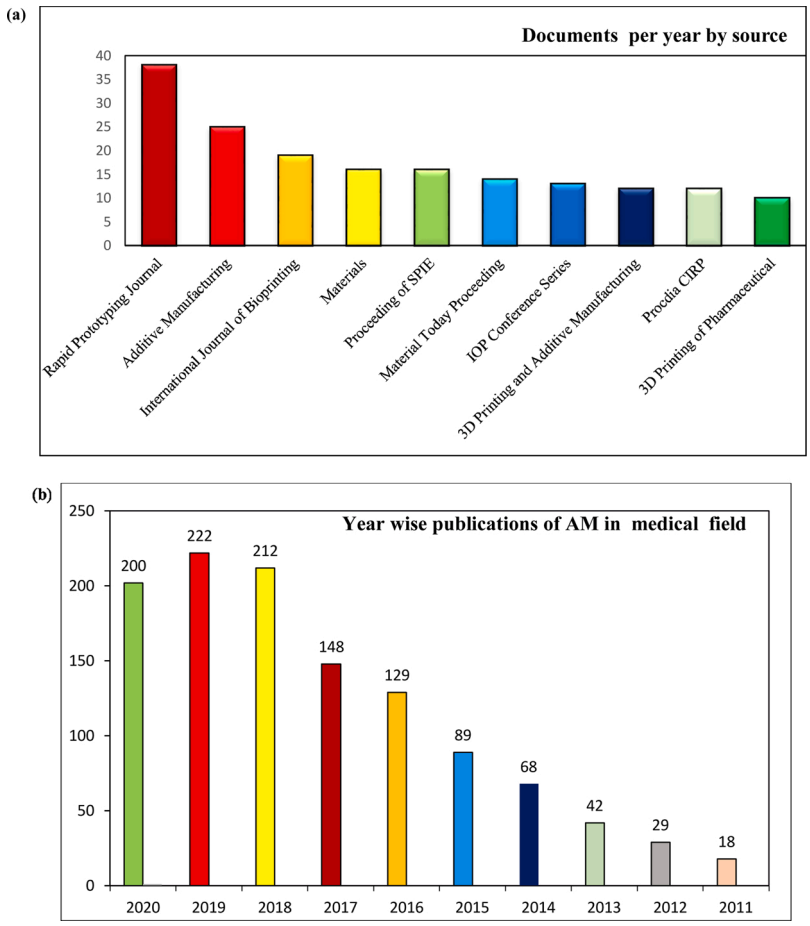

Fig. 4. (a): Additive manufacture applications in medical sector: Top ten journals in which documents are published (Web of Science). **(b)**. Medical applications of AM: Year wise Publication. Source: Web of Science.

and have yet much more to provide over the next 15 years as shown in Fig. 3.

The historical evolution of additive manufacturing goes back to 1980s, by Charles Hull, which he called "stereo lithography". At that time, he was working in manufacturing company at California that manufactured UV lamps into a layer of plastic to put on the surfaces utilized for household application [35]. One day, idea came in his mind to utilize the ultraviolet (UV) light to convert computer aided design (CAD) parts into three dimensional objects. After a lot of experimentation, Hull observed that when ultraviolet light are subjected on photopolymers (acrylic based substance), then it becomes harder. Further, he develops a machine that had an ultraviolet light to engrave the films of acrylic into shapes & stacked the layers up to develop an object. SLA, utilizes a standard triangulation language file format to interpret the data in a computer aided design file, permitting these instructions to be communicated electronically to the three dimensional printer [1]. After many investigations, he starts writing the code that instructs the printer how to engrave the acrylic layers, so he stuck to mostly simple shapes. After eight years (in 1988), he sold 1st 3D printer for $100,000. Later on some companies (Z Corporation, DTM Corporation, Solidscape and Object Geometries) manufactured 3D printers for commercial use. In 1990s the additive manufacturing was 1st applied for medical applications (custom prosthetics and dental implants). Finally, scientists develop an organs from patient's cells and utilized a three dimensional

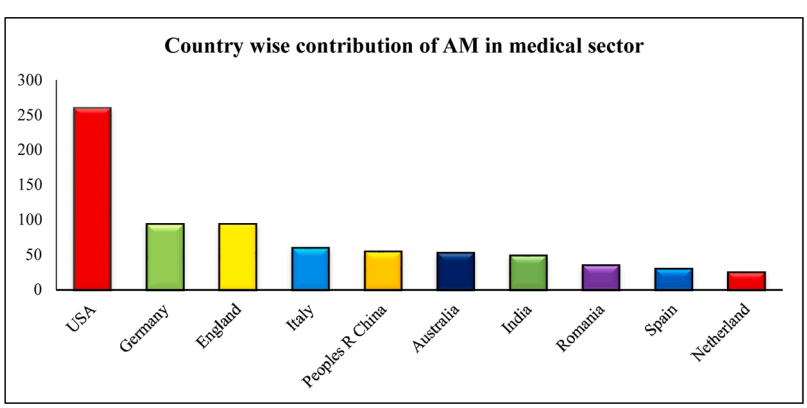

Fig. 5. Applications of AM in medical sector: Country wise contribution (Web of Science Source).

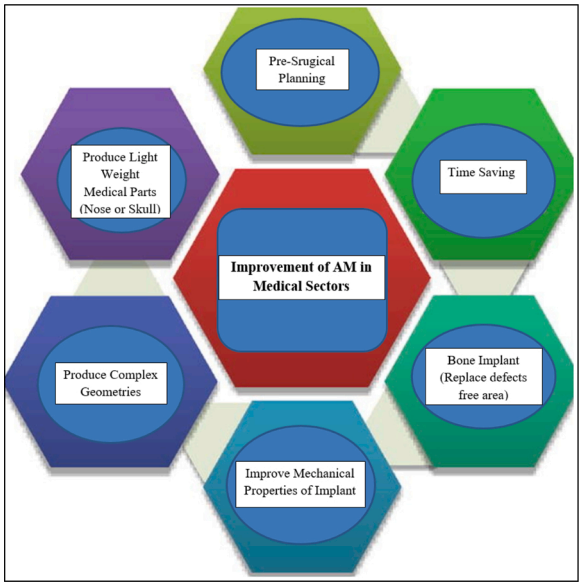

Fig. 6. Improvements of 3D printing in biomedical field.

printed scaffold to support them. In 2008, scientists develop the 1st three dimensional prosthetic leg. In 2012 at Holland, there was a three dimensional printed jaw by a manufacturing company, layer by layer. With the advancement in technology, now, 3D printing machine have become economical, and a generally utilized in hospitals to create human organs. At present, additive manufacturing not only altered the face of medicine, but altering the lives of many terminally ill patients [1].

3. Major improvement of additive manufacturing in medical sector

Various researchers used distinct additive manufacturing processes in distinct areas of medical field. According to the American Professional Association Report the additive manufacturing is estimated to rise by $9.7 billion by 2027 in dental application (increasing 35% annually). The use of 3D printing is also growing day by day especially in medical field. The study reveals that about 11% of medical industries revenue comes from three dimensional printed components, whether medical device or implants. The growing need of additive manufacturing is due to requirements of customize medical parts [36]. According to the web of science data, total 1157 research papers of additive manufacturing for biomedical applications has been published from 2011 to till Oct, 2020 years. The specific detail of research publication of distinct journals and number of research paper published year wise on AM in medical applications is represented in Fig. 4 **(a, b)** respectively. Although, there are number of research publications in this area, but here only top 10 journals are illustrated. Among, these top 10 journals, Rapid Prototyping (RP) Journal have maximum research publications. In addition, the country wise research contribution on additive manufacturing in medical applications is represented in Fig. 5. Among, top ten countries, USA have maximum contribution.

The some significant improvement of AM in medical sector is shown in Fig. 6.

Table 1
Types of materials commonly used for distinct biomedical implant applications.

Type of Metal	Applications	References
316 l SS; Ti; Ti6Al4V CoCrMo; Ti6Al4V; Ti6Al7Nb	Orthopedics: Bone fixation: plate, screw orthopedics: Artificial joints	[39]
316 l SS	Otorhinology: Artificial eardrum	
Poly glycolic acid (PGA)	Internal fixation	[40]
	Graft material	[41]
	Scaffold	[42]
	Interference screw	[43]
Poly lactic glycolic acid (PLGA)	Microspheres & carriers for BMP	[44]
	Scaffolds	[45]
	Composite	[46]
Poly L-lactic acid (PLLA)	Carrier for BMP, composite with HA, scaffolds	[47–53]
Hydroxyapatite (HA)	Composites, Scaffolds, bone fillers, pastes, coatings, drug delivery	[54–65]
Magnesium (Mg)	Implants, osteosynthesis devices, plates, screws, ligatures, and wires.	[66–81]
Tricalcium Phosphate (TCP)	Bone fillers, injectable pastes, cements	[82–94]
Poly caprolactone (PCL)	Scaffolds and composites with HA fillers	[95–100]
Stainless Steel	Implants, plates, mini–plates, screws	[101–104]
Ti alloy	Implants, screws, plates, BMP arriers, orthognathic surgery, mid-facial fracture treatment	[105–112]
Bioglass	Bone defect fillers	[113–119]

4. Biomedical materials, mechanical properties and their applications

There are several of materials which may be utilized for medical applications of 3D printing. The selection of material is mainly depends on the utility/properties required in the production of final part or AM model i.e. customized implants, surgical tools, prosthetic limbs, tissue scaffolds etc. For medical applications where strength, durability and flexibility are more important, then acrylonitrile butadiene styrene (ABS) and nylon is a good choice [37]. However, polylactic acid (PLA) is

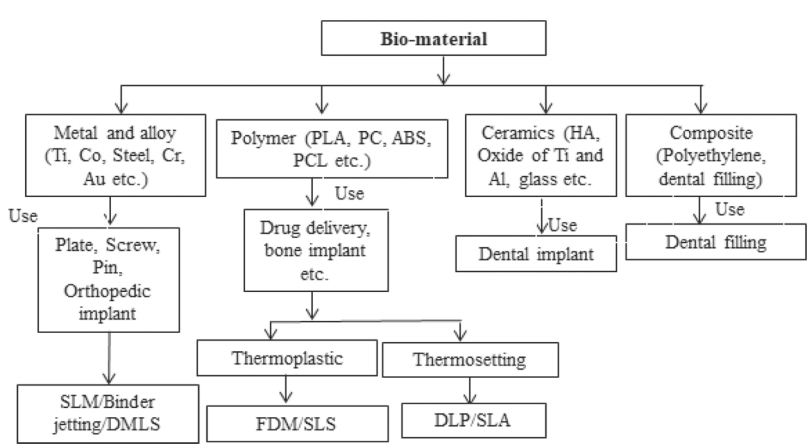

Fig. 7. Classification of AM material.

Table 2a
Mechanical properties of commonly used implant material.

Materials	Alloy (Material type)	Mechanical properties				Ref.
		Yield strength (MPa)	Ultimate tensile strength (MPa)	Young modulus (GPa)	Max. elongation (%) age	
Stainless* steel	316 l type (ASTM, 2003)	190	490	193	40	[120]
CoCr alloys*	CoCrWNi (F90) (ASTM, 2007a)	310	860	210	20	[121]
	CoNiCrMo (F562) (ASTM, 2007b)	241	793	232	50	[122]
Ti and its* alloys	Pure Ti grade 4 (F67) (ASTM, 2006)	485	550	110	15	[123]
	Ti6Al4V (F136) (ASTM, 2008)	795	860	116	10	[124]
Degradable metals*	Pure iron (Good fellow,2007)	150	210	200	40	[125]
Degradable metals	WE43 Mg alloy (ASTM, 2001)	150	250	44	4	[126]
Degradable metals	WE43 Mg alloy, temper T6 (ASTM, 2001)	170	220	44	2	[126]
Degradable metals	Fe35Mn alloy, powder sintering thermo-mechanical treatment	235	550	N/A	32	[127]
	FeMnPd alloy, cast + heat Treatment	850	1450	N/A	11	[128]
Degradable metals	Magnesium, annealed sheet (ASM, 1998b)	90	160	45	3	[129]
	MgZnMnCa alloy, cast	70	190	N/A	9	[130]
	MgCa alloy, extruded	140	240	N/A	11	[131]

* Under annealed condition.

Table 2b
The mechanical and physical property of distinct implant materials in comparison to natural bone.

Material	Mechanical characteristics				Ref.
	Modulus of elasticity (Gpa)	Toughness (MPa)	Compressive yield stress (Mpa)	Density (g/cm3)	
Natural bone	3–20	3–6	130–180	1.8–2.1	[132]
Magnesium	41–45	15–40	65–100	1.74–2.0	
Co–Cr alloy	230	–	450–1000	8.3–9.2	
Stainless steel	189–205	50–200	170–310	7.9–8.1	
Synthetic hydroxyapatite	73–117	0.7	600	3.1	

suitable biodegradable material in medical field. The classification of distinct biomedical materials are presented in Fig. 7

An ideal biomaterial should be easy to print, biocompatible, morphologically mimic living tissue, nontoxic etc. These biomaterials are used for distinct biomedical applications. The metal and alloys are used for where high strength part is required such as in orthopedic implants, plates, screw etc. The ceramics material is suitable for bioactive orthopedic implant. The material used in biomedical is the composite, which is used for Porous orthopedic implants owing to better mechanical properties. However, polymers are most widely used material is medical field. Among all biomaterial, polymer based material is highly used (86%) [38].

Although, the selection of material for distinct biomedical applications is depends upon specific implant applications. Some commonly used materials for different biomedical field is given in Table 1.

The mechanical properties of some of the material used for distinct biomedical applications are shown in Tables 2a–2e.

However, the biomimetic materials are also used in tissue engineering applications. The designing enhancement of scaffolds through conventional method (Salt leaching & Phase separation) is conducted by distinct researchers. However, the distinct process methods such as rapid prototyping (RP), electrospinning etc. already have been utilized for manufacturing of three dimensional biomimetic scaffolds. Hence, bone tissue engineering play important role in the damaged tissues and harvested treatment. The ceramics wollastonite bredigite as well as polymers (polycaprolactone, poly (lactic co-glycolic) acid are extensively used in bone tissue engineering [161–170].

The several researchers experimentally studied distinct AM methods using invitro testing for biomedical applications such as medical education, surgical planning etc. The distinct AM methods contribution towards distinct categories of disease treatments are explained in Table 2e.

4.1. Functionally graded material (FGMs) and its applications

The materials with changing microstructure, composition and mechanical properties across the volume of the material are known as FGMs. In 1984, Japan was the 1st country that develops the scientific term of functionally graded material. These composite materials recently considered as novel, smart or advanced quality material, because it withstand high temperature, decreased stress intensity factor and offers good distribution of residual stresses etc. In addition, these materials properties (thermal, mechanical) gradually changes from one layer of material to another layer of material, to full fill the intended function which is needed especially for aerospace as well as power industries etc. [184–186]. FGMs initially utilized as thermal barrier materials for fusion reactors, combustion chamber, turbine blades, space vehicles and aerospace structural applications, but currently these materials are considered as a potential structural material candidate for aerospace and high speed automotive application. These composite materials have the properties of resistance against fracture & erosion corrosion (EC), which is the modern requirement of the industry [187]. The different types of FGMs manufacturing techniques are categorized into distinct groups [188–193] as dedicated in Fig. 8. The classification figure provides guidelines for part manufacturer to help them in choosing the best FGMs fabricating technique which fulfill the technical requirement.

The development of FGMs are manly depends upon types of process parameters used for manufacturing of these materials [193]. The examples of some FGMs manufacturing parameters and their historical development are shown in Fig. 9 **(a, b)**.

Among all functional graded materials manufacturing techniques the solid state technique especially four classes of AM processes (Material extrusion; sheet lamination; Powder-bed fusion & Directed-energy deposition) are most promising techniques for the manufacturing of

Table 2c
The mechanical property (porosity) percentage of distinct metal/ceramic composites used for scaffold fabrication.

Author/Year	Metal/ceramic	Type of Study	Porosity (%)	Reference
Anovitz L. et al. 2015	PLGA-(PEG-ASP)	In vitro/ in vivo	>80	[133]
Manassero M. 2013	Acropora sp.	In vitro/ in vivo	4−12	[134]
Foroughi M.R. et al.2013	P3HB-HA	In vitro	86	[135]
Yu L. et al. 2013	CPC/BioglassR	in vivo/ In vitro	Micro porosity	[136]
Teraoka K. et al. 2013	Hydroxyapatite HA	in vivo/ In vitro	50	[137]
Liu L. et al. 2013	Bioactive glass	In vitro & in vivo	47	[138]
Mondal D. et al. 2012	ZrO2–CP/PCL	In vitro	78	[139]
An H. S. et al. 2012	ZrO2/HAP	In vitro/ in vivo	72–91	[140]
Martel-Estrada S.A. et al.2012	PCLF-PVA-HA	In vitro/ in vivo	80	[141]
Erol M.M. et al. 2012	SiO2/CaO/Na2O/ MgO/B2O3	In vitro	85	[142]
Kushwaha M. et al. 2012	Niobium/ fluorapatite	In vitro	Macro porous structure	[143]
Riccio M. et al. 2012	Silk fibroin	In vitro/ in vivo	85 ± 5	[144]
Seyednejad H. et al. 2011	PCL or pHMGCL	In vitro	69.7-PCL	[145]
Deng M. et al. 2011	PPHOS/PLAGA	In vitro	87.2	[146]
Tiainen H. et al. 2010	TiO2	In vivo	80–90	[147]
Nanda kumar A. et al. 2010	PEOT/PBT-CP	In vitro/ in vivo	68.5 ± 2.2	[148]
Fernandez J.M. et al. 2010	PCL/PDIPF	In vitro	70	[149]
Nandi S.K. et al. 2010	Chitosan	In vivo	85 ± 2	[150]
Grafahrend D. et al. 2010	PLGA-PEO	In vitro	64	[151]
Idris S. et al. 2010	poly(LLA-co-CL)/ poly(LLA-co-DXO	In vitro	90	[152]
Wu C. et al. 2010	CaMgSi2O6	In vitro	300	[153]
Geng F. et al. 2009	βTCP/Mg	In vitro	42−50	[154]
Fassina L. et al. 2008	Titanium fiber-mesh sheets	In vitro	40 ± 3	[155]
Reiner T. et al. 2008	Ti wires	In vitro	40	[156]
Cui L. et al. 2007	Natural corals (China, Hainan)	In vitro/ in vivo	57 ± 6.5 vol	[157]

Table 2d
The mechanical property (compressive strength) of distinct metal/ceramic composites used for scaffold fabrication.

Author/Year	Metal/ceramic	Type of Study	Compressive strength (MPa)	References
Liu L. et al. 2013	Bioactive glass	in vivo/ In vitro	86 ± 9	[138]
Baino F. et al. 2013	BioglassR & CEL2-derived	In vitro	2.5–4.5	[158]
Xie H. et al. 2012	K/Sr–CPP	In vitro	1.51 ± 0.47–2.40 ± 0.27	[159]
An H. S. et al. 2012	ZrO2/HAP	In vitro/ in vivo	2.5–13.8	[140]
Tiainen H. et al. 2010	TiO2	In vivo	2.5	[147]
Wu C. et al. 2010	CaMgSi2O6	In vitro	1.36–0.2	[153]
Wu C. et al. 2009	45S5 BioglassR	In vitro	5.4–7.2	[160]

these materials [194,195]. The various AM techniques according to their use of production of FGMs are explained in the section below.

(a) Material extrusion process (FDM): The FGMs components are produced using fusion deposition modeling method and the properties of produced part are mainly depends upon the process parameters used. The lower machine & equipment cost, material flexibility, ease to use, durable and inexpensive raw material are the merits, whereas high surface roughness, prints quality are not good as those by SLA or SLS and lower mechanical strength are the major drawback of this technology [196–199]. The schematics diagram of FDM technique is shown in Fig. 10.

This is one of the important AM process for manufacturing of FGMs. In this technique the unwound plastic material in semi liquid form is injected through extrusion nozzles tip, onto a base in layers to fabricate a desired components [201]. Lue et al. (2002) [202] used FFF technique to produce a FGMs part. Results revealed that there was a compositional change across the graded sample.

(b) Powder-bed fusion: It comprises distinct AM processes techniques such as SLM, SLS and EBM. In SLS the laser fuses the powder material, SLM laser completely melts the powder whereas EBM process required vacuum for the development of FGMs components [203–205]. The Schematic diagram of EBM method as shown in Fig. 11.

Trainia et al. [208] studied mechanical properties, surface roughness, chemical composition and microstructure of Ti alloy implant manufactured by SLS technique. The results indicated that the this process technology is an effective process for manufacturing dental implants with functional graded materials that exhibit superior elastic characteristics which is very near to those of the human being bone. Sudarmadji et al. [209] used SLS technique to study the functionally graded scaffold. Form the deep analysis it has been proven that SLS is an effective manufacturing method for FGM implants.

(C) Directed-energy deposition (DED): This process technology used energy in the form of electron beam, laser and plasma arc to manufacture FGMs components. In this process either building base is moved while, deposition head remain stationary and vice versa. Laser metal deposition technique is also deals with the class of DED method, used to develop functional parts made of FGMs, metal and alloy etc. LMD technique utilized laser beam of powder/wire material to create a melt pool on the substrate to develop a part in layer by layer fashion [210–217]. The schematic presentation of DED process is depicted in Fig. 12.

(D) Sheet Lamination: Sheet lamination technique was 1 st introduce in market in 1991 by Helist company. Laminated object manufacturing (LOM) is an example of this process technology, which is used for manufacturing of FGMs prototypes. It is also considered as economical and fast solid state technology. This process was invented by Helisys that utilizes sheets of material such as metal or plastic or paper and are cut using blade or laser with each sheet showing a slice of CAD model. After the cutting of sheets binder is used to for stacking and bounding purpose and cut sections are removed [218–221]. The schematic illustration of LOM method and process flow chart is depicted in Fig. 13 **(a, b)**.

Applications of FGMs: FGMs have proven their position among recent advanced materials. They became a hard competitor in wide cluster of uses, such as aviation, defense, medical and energy sector. The low cost, process repeatability and reliability are the future frontier for functional graded materials. According to the field of applications FGMs can be categorized into following groups [222,223] as depicted in Fig. 14.

The FGMs biomaterials play an important role in organic systems. It can provide structural as well as biological functions. The importance of AM manufactured functional graded material for distinct biomedical

Table 2e
The contributions of distinct categories of AM method in vitro studies for biomedical applications.

Author/ Year	Technique	Applications	Summary	Ref.
Sanghera B. et al.2006	FFF	Knee, mandible, hip, radiotherapy face mask, wrist, shoulder etc.	For good understanding of the problems Patient-specific models were manufactured/ fabricated	[171]
Holmer B. et al.2005	SLS	orthopedic product	Additive manufacturing decreased the product fabrication time & manufactured patient specific surgical precisely.	[172]
Ripley B. et al. 2016	SLA	Trans catheter aortic valve prototype for the study of replacement	Manufactured prototype with a high dimensional accuracy of 0.1 mm from the computer aided model generated from computer tomography scan.	[173]
Pietrabissa A. et al. 2016	Polyjet	Laparoscopic splenectomy	For education purposes the complex anatomy structure was 3D printed and also able to Reproduce small vessels.	[174]
Hieu L.C. et al. 2003	NURB & STL	Cranioplasty implant	Fabricated implant by using Reverse engineering and CT data.	[175]
Hochman J. B. et al. 2015	FFF	Cadaveric temporal bone	For operation planning study, prototype was Fabricated that help to minimize the risk.	[176]
Cohen J. et al. 2016	FFF	Temporal bone	Fabricated prototype at less cost for the educational training purpose.	[177]
Cohen A. et al. 2009	SLA	Bone graft and dental models	AM technology exhibits a precise, economical mandibular reconstruction, which mainly help to reduce operation time, decreased blood loss and easier surgical procedure.	[178]
Auricchio F. et al. 2016	LOM	orthopedic modelling (bone surfaces)	This technology enables advance testing of the surgical procedure, this help to decrease the operation time.	[179]
Sing S.L. et al. 2016	SLM & EBM	Medical devices (implants & fixations)	SLM and EBM exhibits opportunities to mass customize implants in orthopedics sector with economical cost owing to their ability to manufacturing components with very complex and intrinsic designs that are specific to individual patients.	[180]
Dodziuk D. et al. 2017	–	Hearing aids	3DP provide personalized medicine on the macro scale, As implants, prostheses and many other devices for medical application are patient-specific.	[181]
Tanaka K.S. et al. 2016	FDM	RP exoskeleton	The recent improvements in additive manufacturing have the potential to enhance the customization, accessibility and procurement of devices.	[182]
Whitley D. et al. 2017	DLP	Dental implant guides	The application of desktop additive manufacturing is a practical option for the manufacturing of very precise implant drilling guides.	[183]

applications and types of distinct conventional FGMs process methods and their applications are presented in Tables 3a and 3b respectively.

4.2. Major applications of 3D printing in medical field

Additive manufacturing has a wide range of medical applications. However, at present it is most widely used for making three dimensional reconstructions of human skull defect, skull model, porous Ti implant produced with EBM technique and Ti implant fitted to the skull model respectively represented in Fig. 15.

The classification of 3D printing in medical sector is shown in Fig. 16.

4.2.1. Bio printing tissues and organs

Bio printing is process that uses a computer-guided pipette to layer living cells known as bio-ink, on top of one another to develop artificial living tissues. At present, bio printing is used to fulfill the need of organs and tissues which is suitable for transplantation. In addition, it is used for generation and transplantation of tissues such as heart tissue, bone, tracheal splints, cartilaginous structures, vascular grafts and multilayered skin etc. [235]. These artificial tissue organoids or constructs can be utilized for medical research as they mimic organs on a miniature scale as they are economical for transplants of human organ. Recently, based on the concept of printing for every method, bio printing is mainly classified into 3distinct types called laser based, IJP or (drop-on-demand printers) and extrusion based. The Comparison of different AM technologies of bio printing on distinct parameters as depicted in Table 3c.

4.2.2. Surgical tools

Additive manufacturing is used for production of distinct orthopedic tools, dental surgical tools and guides (implant supporting bar and abutments). By using this technology, physicians can create guides that precisely follow a patient's unique anatomy and locate surgery instruments very accurately. These instruments can be utilized to operate complex and tinny areas along with full safety to patient [237].

4.2.3. Anatomical models for surgical preparation

Additive manufacturing convert the 2D image (MRI or CT scans) into 3D image. This helps the surgeons in better planning and surgeon training. It is also used for creating patient specific implant organ models that surgeons can utilize to practice on before conducting any complicated surgeries. Anatomical models most widely used maxillofacial,

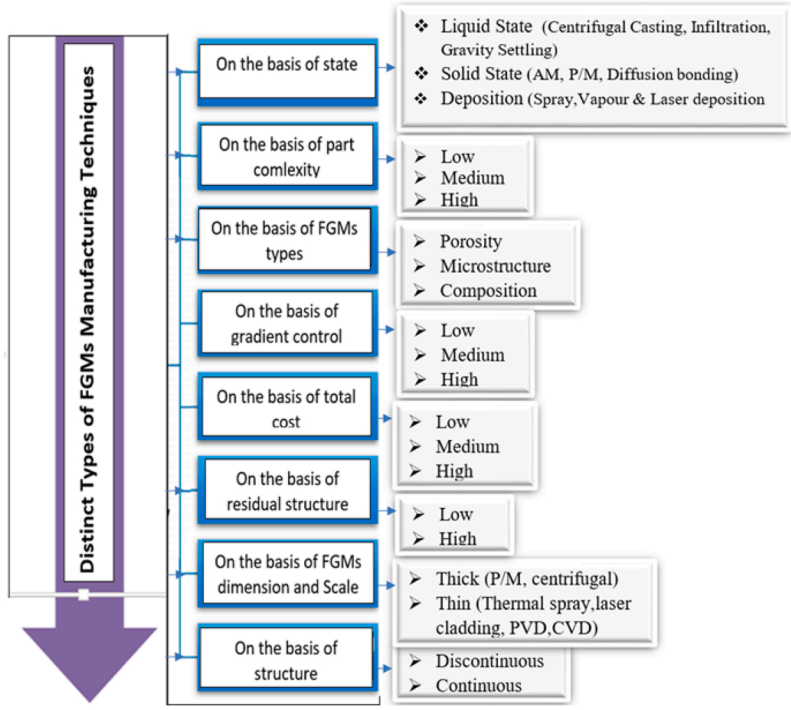

Fig. 8. Types of FGMs manufacturing techniques.

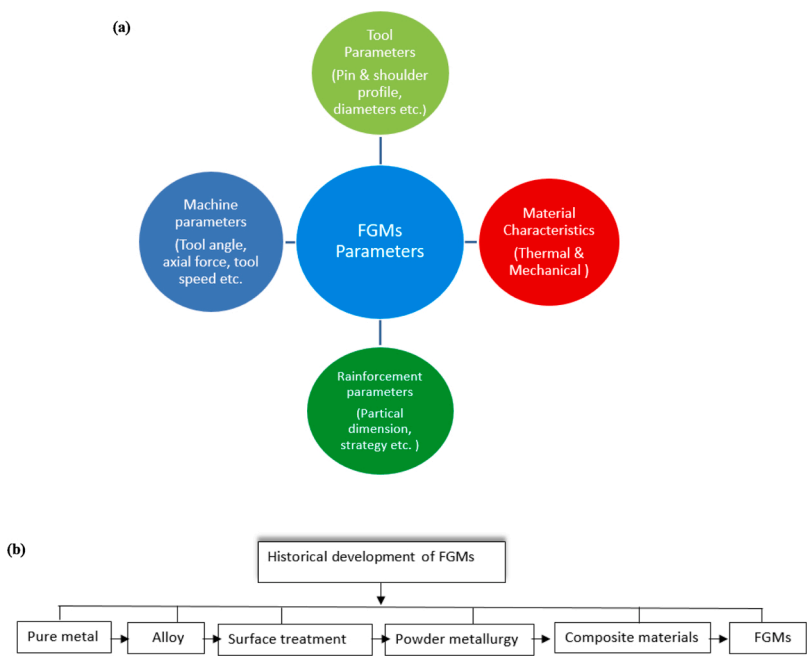

Fig. 9. a). Distinct types of FGMs manufacturing process parameters. **(b).** Historical development of FGMs.

orthopedics and neurological surgery. In addition in medicine, they are widely used for planning treatment, assisting diagnosis and manufacturing implants etc. [238].

4.2.4. *Custom-made implants and prosthetics*

This technology is also utilized to develop prosthetic limbs that are customized to suit and fit the wearer. It speeds up the process and it produce economical products that provide patients the same functionality as produced by conventional methods.3D printing is very effective in producing customized implants and prostheses and solve many orthopedics problems. The custom made implants include Maxillofacial Implants, Cranial Implants, Mandible Implants, and Orthopedics Implants etc. [239].

In addition, in medical sector the 3DP has several applications include: scaffoldings & tissue engineering [240,241], mechanical bone replicas [242], forensics [243], surgical planning [244], design of medical instrument [245] and customized implant design [246].

4.2.5. *Tissue engineering*

Bone defects, injuries, harmful diseases, accidents damage tissues and emanate the loss in the working of joints and organs in the human body. To restore the working of injured joints the surgery is generally

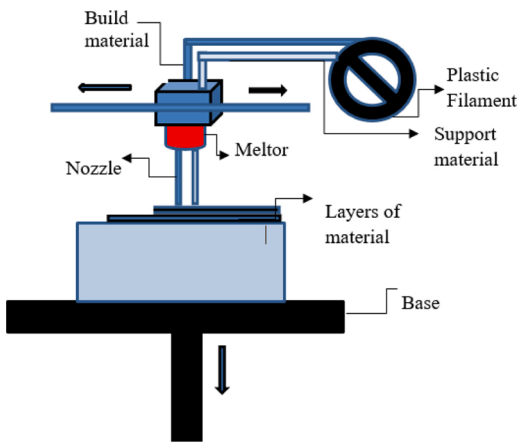

Fig. 10. Schematic illustration of FDM process technique [200].

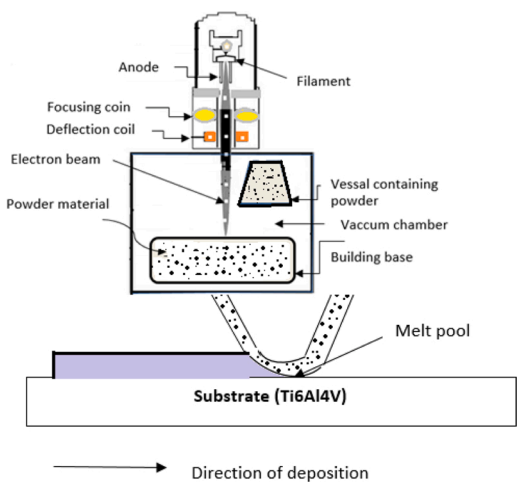

Fig. 11. Schematic illustration of EBM process [206,207].

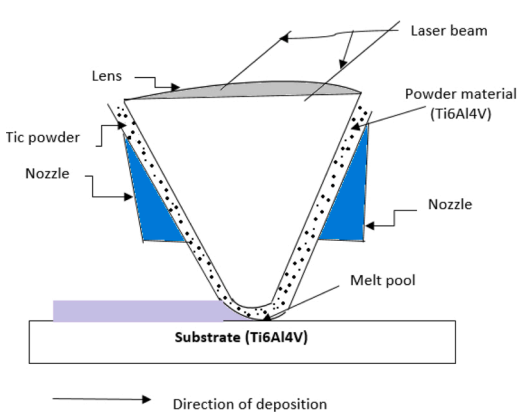

Fig. 12. Schematic presentation of DED process method [216].

needed for repair & replacement of implants [247,248]. In tissue engineering applications the distinct techniques (gas foaming, freeze-drying, electro-spinning, solvent casting, emulsification are used to manufacture scaffolds. The application of 3D printing in medicine can exhibit lot of merits such as, low cost, customization & personalization of medical parts, improved collaboration, democratization of design and fabrication etc. [249]. There are several types of biomaterials used for different applications of tissue engineering in 3DP technology as presented in Table 4.

However, the other applications of tissue engineering include; Bone, Skin, Nerve, Vascular, Cardiovascular, Meniscus, Urethra etc. Some examples of polymer used for tissue engineering are represented in Table 5.

4.2.6. Dentistry application

The vast applications of AM process technology, in medical sector are the dentistry, which includes oral and maxillofacial surgery, orthogenetic, endodontic and orthodontic etc. This technology provided high quality of restoration as well as comfort to dentists. In addition, dental restorations, which are being created through AM, are more robust in production than restorations created by dental technicians. The distinct AM techniques (FDM, SLS, LOM) are used to print dental pieces and produces bridges, orthodontic appliances, crowns etc. [268,269]. The distinct AM material and their applications for dental are presented in Table 6.

In addition, oral surgery is novel approaches which helps for surgen simulation/planning and also provide overview to surgen before starting the patient surgery [271].

4.2.7. Clinical applications in traumatology and orthopedics

It is the 1st medical sector to use AM method to manufacture PS models, as well as maxillofacial surgery. Orthopedics is generally considered as surgical discipline, deals with biomedical engineering, which has been tested in orthopedic disciplines such as joint arthroplasty, trauma surgery, deformity improvement etc. AM produced models and play an important role mainly for surgen training, surgical planning and decreasing the re-operation rate. The major applications in traumatology and orthopedics include Surgical guides, Biomaterials, Implant (PS Implants and orthoses Implants), Orthoses, Traumatology, Orthopedics etc. [272–278]. The different clinical applications and their merits in different field are presented in Table 7.

4.2.8. Pharmaceuticals

Distinct AM methods used in pharmaceutical sectors are Inkjet based, laser-based, and nozzle-based printing methods [285]. Goyanes, et al. (2016) revealed that owing to the production of antiacne device, SLS technique is better as compared to FDM, because SLS contain salicylic acid, which provide greater thermal stability, drug-loading capacity and resolution [286,287]. The tablets manufactured by AM techniques generally classified into two groups (single API and multiple API tablets). The distinct categories of drugs, dosage form and AM techniques used in pharmaceuticals as shown in Table 8.

Among all AM techniques inkjet based techniques are most widely used in pharmaceutical industry. The folic acid, vancomycin, paclitaxel are the examples of active ingredient whereas acetone, glycerin, propylene glycol are considered as inactive pharmaceutical ingredient [297]. In pharmaceutical sector additive manufacturing have many advantages such as Customization & personalization, high productivity, high resolution, high accuracy, reliability, minimize manufacturing cost, allows controlled size of droplets, strength of dosage, complicated drug release profiles, multi-dosing etc. [298–303].

Now a day, AM process technology used printing is mostly used for the generation of different categories of functionalized micro-needles. The applications of AM technology used to fabricate the patches of transdermal drugs as depicted in Fig. 17.

4.2.9. 3D printing of medical device

AM commercial available devices grouped into three different classes as depicted in Fig. 18.

The role of surgical instrument and guides is very important in medical industry. In surgical tool such as retractor, hemostats and medical clamps are generally used and easily fabricated using AM technology. Recently, in dentistry because of high accuracy and customization surgical instruments are mostly preferred [306,307]. The

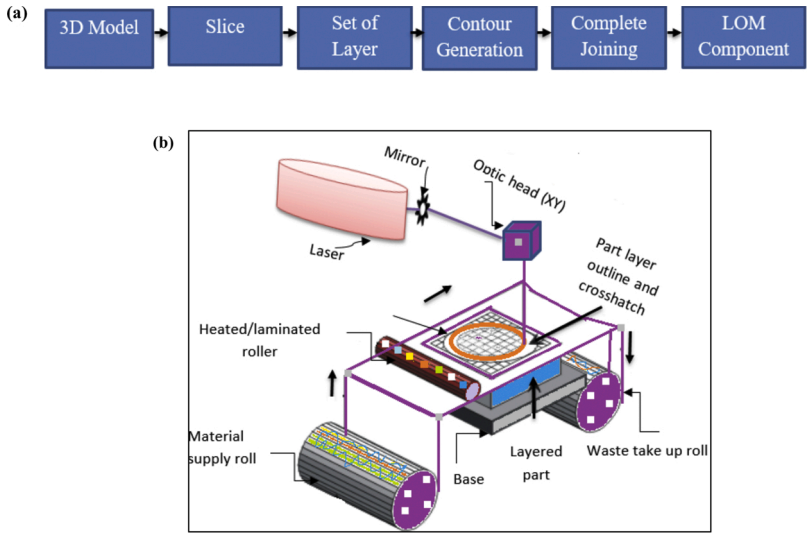

Fig. 13. **(a)** Flow chart of LOM process method [220]. **b)** Schematic diagram of LOM process method [220].

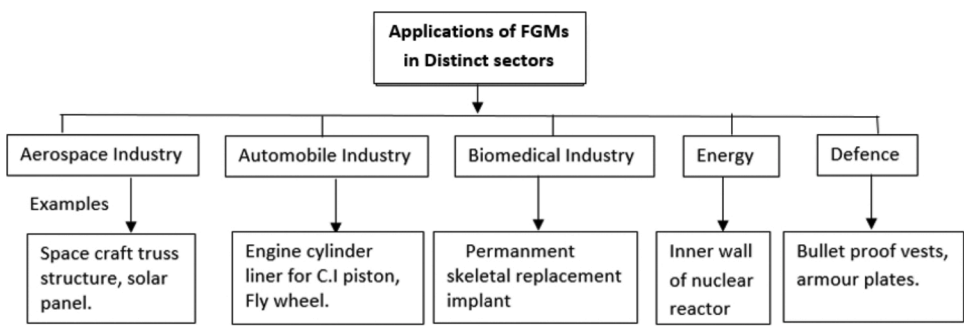

Fig. 14. FGMs applications in distinct sectors [222].

Table 3a
Importance of AM manufactured functional graded material for distinct biomedical applications [224–227].

Author/Year	Techniques /FGMs used	Field of applications
Bakarich, S. et al. 2017	Material extrusion Alginate/poly acrylamide	Artificial tendons
Han, C. et al. 2018	Selective laser melting/ Ti/HA	Orthopedic
Chen, B. et al. 1992	Stereo lithography/ Soft elastomeric to hard brittle polymer to FG ceramic composite.	Artificial muscles, bio-mimetic materials.
Bakarich, S.E. et al. 2014	Alginate/acrylamide gel precursor solution	Artificial organs, tissue scaffolds and artificial muscles.

Table 3b
Types of distinct conventional FGMs process methods and their applications [228–233].

Process/Technique	Material used	Application
Solid phase: Spark plasma sintering	B4C, ZrO2 and ZrB2-SiC/ZrO2	Cut/hard/ wear resistance material.
Gas phase: Thermal spraying method	CeO2-Y2O3-ZrO2, Polyimide/WC-Co etc.	Military and aerospace.
Liquid phase: Electrophoretic deposition method	Ti-6Al-4 V, WC/Co and ZrO2/Al2O3 etc.	Ceramic appliances.

major examples of medical devices are presented in Fig. 19.

4.2.10. DP in physiotherapy

Athletes are generally facing injuries in the elbow, knee, and back, caused by fascia. However, Osteoarthritis in knee joint also faced by the old people, and traditional method is used to treat these problem. To overcome from the Osteoarthritis, a guide is printed which is fitted inner portion the knee by a surgery is used. The printing process of ultrasound physiotherapy orthosis is describe here. Firstly, Artec Eva device is used for scanning of patient hand. However, to develop a CAD model (mesh mixer) the collected data is utilized. The SLS process technology is used to fabricate a 3D model. The printed models consist of two components. The 1st part is used for fixing the limb and 2nd part for ultrasonic generator. Ultrasound physiotherapy have many merits such as restoration, regeneration and anti-inflammatory of nerve fiber etc. [308–311].

AM play an important role in every year and widely used in health sector. In addition another applications includes: cardiothoracic surgery [312], gastroenterology [313], cardiology [314], oral and maxillofacial surgery [315], neurosurger [316], orthopedic surgery [317], plastic surgery [318], otolaryngology [319], podiatry [320], radiation oncology [321], pulmonology [322], and vascular surgery [323]. Zhang et al. [324] used additive manufacturing to design and manufacture the custom joint prostheses on the basis of osseous morphology of resected proximal tibial osteosarcomas. The postoperative diagram/images of a custom prosthetic reconstruction is depicted in Fig. 20. The custom joint prosthetic reconstruction has presented better outvomes for patients with osteosarcoma in the proximal tibia or the proximal tibiofibular joint during limb salvage operations and neoadjuvant chemotherapy.

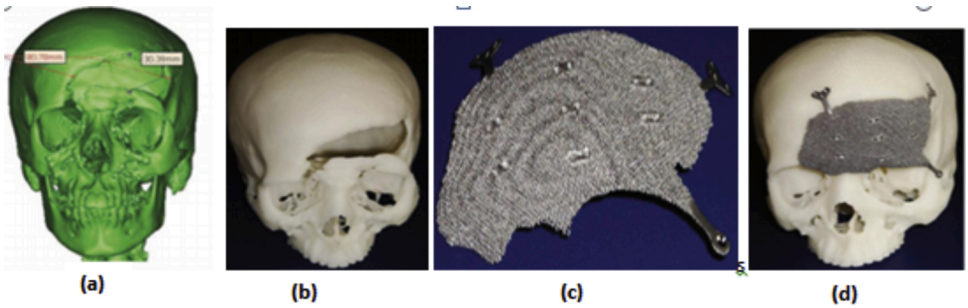

Fig. 15. Representative images of applications of AM in medical sector: (a) 3D digital reconstruction of skull defect. (b) Skull model. (c) Porous Ti implant fabricated with EBM. (d) Ti implant fitted to the skull model [234].

Galasso et al. [325] implanted a custom distal femur modular prosthesis into a patient of twenty year old with stage IIB osteosarcoma. After the end of 10 months surgery the knee range of motion reached 0° to 110°. In addition the patient could become able to bear full weight without any support and pain.

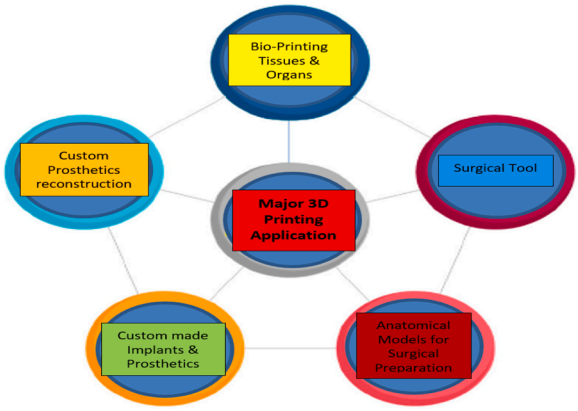

Fig. 16. Applications of AM in medical Sector [235].

Table 3c
Comparison of different additive manufacturing technologies of bio printing on distinct parameters [236].

S. No.	Parameters	Laser Printing	Inkjet Printing	Micro extrusion
1	Biomaterial	Hydrogels and nano-hydroxyapatite	Alginate, fibrin & hydrogels	Alginate, collagen, fibrin & hyaluronic acid
2	Resolution	50 μm	50–300μm	100 μm to 1mm
3	Cell viability	>85%	>85%	40–80%
4	Printing speed	200–1600 mm/sec.	1–10,000droplet/sec.	10–50 μm/sec.
5	Material viscosity (mPa/s)	1–300	3–12 (low)	$(30–6 \times 10^2)$ High
6	Manufacturing time	Long	Medium	Short
7	Applications	Skin	Skin, cartilage and vascular	Trachea & Cardiac valve

4.3. Comparison of distinct AM techniques

There are distinct 3DP techniques used in printing of medical parts are compared in Table 9.

The results of various researcher used distinct additive manufacturing processes in medical sector are summarized in Table 10.

The major fundamental aspects of smart 3D printing technology as presented in Fig. 21.

Analytical techniques for process monitoring in metal 3D printing

Table 4
Distinct types of biomaterials and their applications for tissue engineering.

Author/Year	Biomaterials used	Field of applications	References
Cheng, et al. 2016	Hydroxyapatite (HAp)	Customized scaffolding	[250]
Elomaa, et al. 2011	(Polyether ether ketone) PEEK	Regenerative medicine	[251]
Laumer et al. 2015	Nylon	Implants	[252]
Gmeiner, et al. 2015	Bioactive glass	Customized scaffolding	[253]
Salmoria, et al. 2007	Polyethylene	Customized scaffolding	[254]
Serra, et al. 2013	(Poly lactic acid) PLA	Regenerative medicine	[255]
Mu, et al. 2016	Glucose	Regenerative device	[256]
Li, et al. 2015	Polystyrene	Regenerative medicine	[257]

Table 5
Examples of polymer used for tissue engineering.

Author/Year	Tissue	Polymer used	Study Type	References
Loozen, et al. 2013	Bone	Alginate	In vitro and In vivo	[258]
Cui, et al.2016	Bone	PLA fibers and GelMA	In vitro	[259]
Saito, et al. 2015	Bone	PLLA, PCL	In vitro and In vivo	[260]
Cubo, et al. 2016	Skin	Fibrin	In vitro and In vivo	[261]
Michael, et al. 2013	Skin	Matriderm	In vitro and In vivo	[262]
Lee, et al. 2017	Nerve	PEGDA	In vitro	[263]
Lee, et al.2009	Nerve	Collagen	In vitro	[264]
Huang, et al. 2018	Vascular	PCL	In vitro and In vivo	[265]
Chen, et al. 2014	Cardiovascular	PCL	In vitro and In vivo	[266]
Bahcecioglu, et al. 2019	Meniscus	PCL	In vitro	[267]

Table 6
Distinct AM materials and their applications in dentistry [270,271].

Material	Dental applications
ABS, PLA, PC, PEEK	Cost effective models of simple anatomical components
Ceramic filled resins	orthodontic devices, surgical guides and bridges etc.
Alumide powder, polyurethane rubber	Copings & bridges, metal crowns etc.
Photopolymers	Production of craniomaxillofacial implants, drilling & cutting guides.
Photopolymer resins, alginate	Cell-laden scaffolds (tissue printing)

Table 7
Distinct clinical applications and their merits [279–284].

Type of Clinical applications	Merits
Transdermal drug	Drug loading capacity, more temperature stability.
Soft-structured implant	Enhanced cells of organs function
Hard-structure implants	Good surface finish, high accuracy, used for developing more porous implants.
Surgical tools	Minimize tool cost

Table 8
Distinct types of dosage forms and technology used in pharmaceuticals [288–296].

Authors/Year	Type of drug	Type of dosage form	Types of AM technology used
Muzna, S. et al. 2018	Enalapril maleate	Tablet	FDM
Sandler, N. et al. 2014	Hydroxyapatite	Implant	FDM
Melocchi, A. et al. 2015	Furosemide	Capsules (Mediate & Intermediate & release)	FDM
Khaled, S. et al. 2015	Captopril	Tablet	Extrusion based AM technology
Wang, J. et al. 2016	4-Aminosalicylic acid	Oral modified release tablets	SLA
Gu, Y. et al. 2016	Rifampicin	Implants	IJP
Ross S. et al. 2015	Insulin	Microneedle	IJP
Hollander J. et al. 2016	Poly-di-methyl-siloxane	Tablet	Estrusion based AM technology
Tarcha P. et al. 2007	Rapamycin	Tablets	IJP

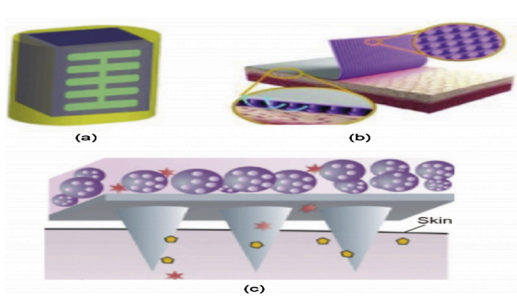

Fig. 17. Applications of AM technology in pharmaceutics to manufacture different categories of drug formulations (a) Tablets of oral medicines [304] (b) Patches of transdermal drugs [305] (c) microneedles of transdermal drugs [305].

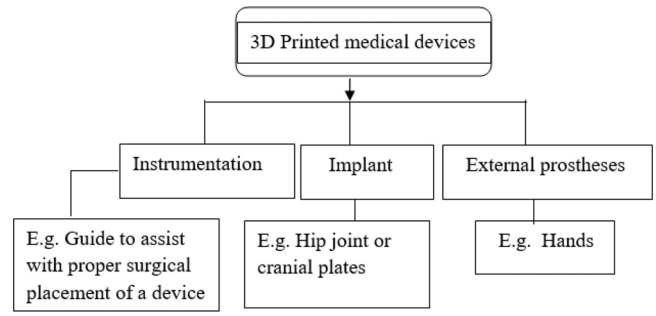

Fig. 18. Commercial available AM fabricated devices.

are presented in Table 11.

4.4. Merits and challenges of AM in medical sector

The majors merits of 3D printing in medical sector is shown in Fig. 22.

4.5. Merits of AM in medical field

4.5.1. Personalization & customization

The word personalization means to fulfill the customer's demand efficiently and effectively and making interactions easier and faster, hence increasing customer- satisfaction. Whereas, customization is the action of modifying something to suit/fulfil a particular individual or task. The custom made implants, surgical tools and fixtures can have a + ve effect in terms of time needed for surgery, patient recovery time [352].

4.5.2. Cost effective

Additive manufacturing is able to produce product/items economically. The cost of 3D printing is less for small dimension implants or prosthetics such as those used for dental and craniofacial disorders. In addition additive manufacturing also decrease the fabricating costs by decreasing the application of unnecessary resources. Some drug may also be printing in dosage form that is easier and highly cost effective to deliver to patients [352].

4.5.3. Improved productivity

3D printing technology is faster as compare to traditional techniques of producing products like prosthetics and implants, which needed forging, milling and a very long delivery time. In addition, speed, reliability and resolution of additive manufacturing method are also improving [352].

4.5.4. Collaboration and democratization

Due to the rising availability of materials and reducing in cost allow more people, including those in medical fields, to use little more than a 3D printing machine and their imaginations to design and produce novel products for commercial and personal use [353].

4.5.5. Accuracy

The medical model fabricated by 3D printing technology possess higher accuracy and surface finish [354,355]

4.5.6. Flexibility

In additive manufacturing, one material can be replaced with another material to enhance the property of medical implant [356].

4.5.7. Ease of use

The 3D model created by 3D printing is fast and easy to use. Since, no tooling or fixture is required [357].

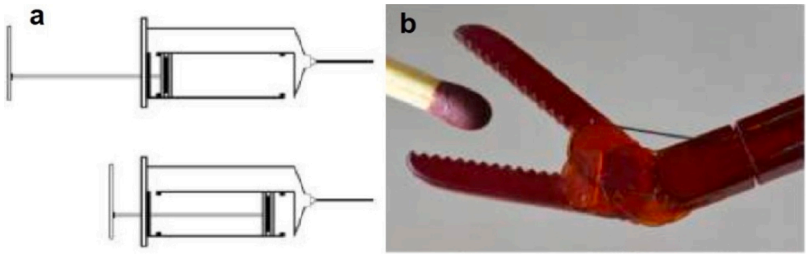

Fig. 19. (a) AM printed double lumen syringe (b) Steerable laparoscopic grasper having 7 DOF [306].

Fig. 20. Postoperative (a) anteroposterior (b) lateral radiographs of custom prosthetic reconstruction [324].

4.6. Challenges of AM in medical field

The Major drawbacks of additive manufacturing in medical sectors are summarized below as presented in Fig. 23.

4.6.1. Cost effective only in case of customized part

This word "mass customization" was 1st raised by Davis in 1980s. Mass customization means ability to produce functional parts that meet the individual customer satisfaction and needs with reasonable cost. Embedded customization, modular production, and customized product services are the major stages of mass customization. Mass customization has become a dominant product manufacturing strategy. The quick changes have become compulsory to most product manufacturing companies in the view of vast competition, globalization, rapid technological innovations etc. AM is cost effective only if the part produced as per the specific need of customer otherwise it is highly expensive and lot of wastage. Customization help to miniature batch sizes and need frequent as well as dynamic re-configuration of the manufacturing system [358–363].

4.6.2. Material changing option is limited

The distinct materials are used for biomedical applications such as titanium alloys, stainless steels, cobalt alloys, cobalt chrome, titanium etc. (Wohlers, 2008). The selection of material for medical implant manufacturing is mainly conducted by bio functionality, biocompatibility, resistance against corrosion etc. The metallic biomaterials often used to replace as well as supporting the parts of the skeleton if we compare these materials with ceramic and polymeric materials it possess high fracture toughness, tensile properties and fatigue strength. The cobalt alloy possess many attractive properties such as resistance against wear, corrosion resistance, heat resistant etc. But the limitation of cobalt alloys is the very cumbersome to manufacture, therefore its applications has been limited (Fig. 23) [364–368].

4.6.3. Limitation in neurosurgery

The more time needed to manufacture a 3D neuroanatomical models demonstrates a clear drawback to the application of model. To make AM printing machine more accessible & appealing to neurosurgeons, the improvements in costs, materials speed and precision are very essential for both AM printing CAD software and hardware [369]. In addition this technology is less suitable for batch production [370], need highly skilled person [371] and less accurate than other machining processes [372,373]. Hence, further search is needed to overcome such drawbacks of 3D printing technology in medical sectors.

Table 9
Comparison of different additive manufacturing technologies and their applications in medical sector [325–334].

Method	Development/ Patented	Process Available	Energy used/ Principle	Merits	Demerits	Materials/resolutions	Cost of 3D printer	Build volume in mm	Layer thickness in mm	Medical applications
FDM	S. Scott Crump	1991	Thermal energy	Cost effective method, part available in distinct colors, no need of post processing and less time consuming.	Poor surface finish, low dimensional accuracy, (poor mechanical properties) low temperature application etc.	Polymers: (PC, ABS, nylon) and Plastics (50−200 μm)	Low	X: <900 Y: <600 Z: < 900	0.15−0.25	RP exoskeleton and medical devices (surgical tools, dental & hearing devices).
SLS	Dr. Carl Deckard	1991	High power laser beam	Post processing option, large /multi range of material options.	Slow printing speed, poor structural property and limited sizes.	Nylon and ceramic(80 μm)	High	X: <200−300 Y: <200−300 Z: < 200−350.	0.06−0.18	Implants & fixations devices such as dental bridges and crowns.
SLM	Fockele and Schwarze	2004	High power laser beam.	Inexpensive and large range of material options	Low speed and limited sizes	Stainless steel, Ti, Al, cobalt chrome, steel. PC, polymers, ABS & wax etc.	High	X: <200−300 Y: <200−300 Z: < 200−350.	–	Dental bridges and crowns.
SLA	Dr. Hideo Kodama	1987	UV laser beam	Simple, produce high quality components, high resolution and complicated shapes.	High cost of machines, fragility and used single material, low strength and durability.	Photopolymer Resin (10 μm)	High	X: <2001 Y: <700−300 Z: < 800	0.05−0.2	Dental implant guides, dental & bone model
LOM	Helisys Inc.	1990	High power laser beam, heat	Versatile, material transportation is easy, economic process.	Post processing is needed, uesful only for plastic & paper, wise range of material cannot use.	Sheet metals, plastic and paper.	High	X: <150−250 Y: <200 Z: < 100−150.	–	orthopedic modelling mainly for bone surfaces
EBM	Arcam	2002	High-power electron beam	Inexpensive and small technology etc.	Costlier, slow process, limited sizes.	Ti, Co Cr, stainless steel, Cu, Al & polymers etc.	High	X: <200−300 Y: <200−300 Z: < 200−350	–	Implants: (dental bridges and crowns).
LMD	Massachusetts Institute of Technology	2002	Laser beam	No need of support material, fast build rate.	Surface quality is less	Cobalt & titanium	High	X: <600−3000 Y: <500−3500 Z: < 350−5000	–	Medicine, medical part repair and build extremely large components.
IJP	Emanuel M. Sachs	2011	Thermal energy OR electricity to heat the ink	Easy to use, Ca3(PO4)2 materials directly to fabricate,	Durability of print head is less, less print speed.	α tricalcium – phosphate powder	High	X: <300 Y: <200 Z: <200	0.013	Scaffolds for tissue engineering applications, maxillo-facial reconstruction.

Table 10
Comparison of distinct additive manufacturing material, process, application, mechanical property and their results.

Author/year	Material	Process	Application	Mechanical property	Results	Ref.
Heller C. et al. (2009)	PLA (Vinyl Esters)	SLA	Scaffold.	Layer thickness = 50 μm, yield = 37–47% in monomer, Elastic modulus for 6 MV = 1.5 GPa and 4DV = 2.4 GPa. Whereas Hardness for 6 MV = 0.9 MPa. and 4DV = 220 MPa. In addition dynamic viscosity for monomer of 6 MV, 12 MM and 4DM = 0.5, 4.3 and 4.4 respectively.	Better biocompatibilities of vinyl esters were observed. In addition the metabolic activity of living cells was calculated by using EZ4 test via photometric measurement	[335]
Bartolomeu F. et al.(2017)	316 l Stainless Steel	SLM HP Casting	Implants.	Hardness = 225 HV, Tensile strength 625 MPa and Yield strength 500 MPa. Hardness = 175 HV, 590 MPa and 300 MPa. Hardness = 170 HV, 450 MPa and 200 MPa.	Result indicates that SLM technique produce high tribological performance and mechanical characteristics for 316 l stainless steel samples. When it is compared to casting and Hot Pressing technique.	[336]
Murr L.E.et al. (2008)	Ti–6Al–4V	EBM	Biomedical/ Biomaterials application.	Mean particle size = 30 μm, Elongation = 16−25%, Max. tensile Strength = 1.15–1.2 MPa, yield strength = 1.1–1.15 MPa and avg. micro indentation hardness = 3.6–3.9 MPa.	Proved that ability to manufacture components Comparable in elongation and strength to the very best wrought Ti–6Al–4 V products.	[337]
Facchini L. et al. (2010)	Ti-6Al-4 V alloy	SLM	Biomedical	Max. tensile strength (hot worked and annealed) = 870 ± 10 MPa, E = 104 ± 2 GPa, E = 104 ± GPa., Yield stress = 970 ± 20, Max. tensile strength for SLM = 1095 ± 10 MPa, E = 110 ± 5 GPa, Max. tensile strength for EBM = 915 ± 10, yield stress = 830 ± 5.	Result indicate the tensile strength of AM component is more as compare to the strength of hot worked components, whereas decrease the ductility.	[338]
Maro P et al. (2018)	PLA/CaCO3 composites	FFF/FDM	surgical guides, orthoses, medical models and casts	Density = 1.23−1.25 g cm^{-3}, amorphous& crystalline structure 67%, 37% respectively.	The results indicated that PLA/CaCO3 composites is based on their thermal properties can be suitable for 3D printing biomedical devices	[339]
Li J. P.et al. (2005)	Porous Ti6Al4V	polymeric sponge replication	Orthopedic	Porosity = 90%, compressive strength = 10.3 ± 3.3 MPa and elastic constant 0.8 ± 0.3 GPa.	Result indicate the porous Ti6Al4V fabricated by polymeric sponge replication technique is very promising biomaterial for implants such as orthopedic.	[340]
Parthasarathy P. et al.(2011)	Functionally graded porous structures	EBM	Biomedical applications	Stiffness = 0.57 ± 0.05–2.92 ± 0.17 GPa, compressive strength 7.28 ± 0.93- 163.02−11.98 MPa and porosities 49.75−70.32%.	Implants designed with this new strategy and fabricated by using additive metal manufacturing technique Would satisfy the long-felt requirements for lighter implants that mainly satisfy the functional as well as esthetic needs of the surgical and patient community.	[341]
Tekinalp H.L. et al. (2014)	Polymer based ABS + carbon fiber	FDM	Biomedical.	Improve tensile strength approx. = 115%, Modulus = 700% and moderate porosity.	Experimental study indicate that the FDM method with its good dispersion capabilities, controlled orientation and the application of carbon fiber-reinforced feedstock has great important for the manufacturing of load-bearing composite components.	[342]
Hwang S. et al. (2014)	ABS + Fe/Cu	FDM	Biomedical	Improve thermal conductivity = 0.646−0.912 W/mK and decrease tensile strength = 45.7−26.5 MPa when the Cu content was added 10–30 wt.%.	Results showed that as increasing the loading of metal particles the tensile stress of composites is decreased. In addition during the printing there is an enhancement in thermal conductivity of ABS material will reduce the distortion of the final desired product.	[343]
Rai B. (2004)	TCP + PCL	FDM	Regeneration on bone.	Improve Bioactivity, Nontoxic and steoconduction.	Result indicates that PCL synergy with rhBMP-2 and bioactive TCP in a novel composite scaffold, could provide an attractive approach for regeneration on bone.	[344]
Heer B.et al. (2017)	SS316+BN	LENS	For composite's surface	Hardness = 178 ± 13 HV, resistance in wear rate = 2.30 ± 0.04 9 10^{-4} mm3/Nm.	Results show the applicability of resistance in wear, metal ceramic composite coating in parts that undergo repeated wear degradation, without compromising large properties of the material. Experimental results indicate that laser processing and BN reinforcement parameters can positively affect the surface characteristics of the structures.	[345]

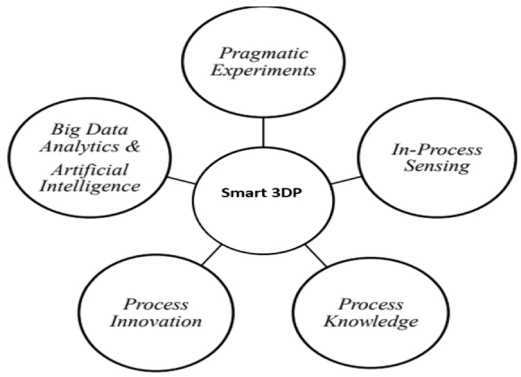

Fig. 21. Fundamental aspects of smart 3D printing process technology.

Table 11
Overview of analytical approaches in metal 3D printing.

Author/Year	Process Sign.	Generation approach	Defects	Analytical technique	Reference
Li, et al., 2019	Temperature and vibration	Accelerometers, thermocouples etc.	Surface roughness	Ensemble learning algorithm	[346]
Scime, et al.,2018	Powder spreading	Stock camera	component failure	Computer vision unsupervised learning	[347]
Zhang, et al. 2017	Powder spreading	Discrete element technique	Shape/configuration	Neural network	[348]
Kanko, et al. 2016	Track geometry	Interferometric imaging	porosity	Plotting	[349]
Clijsters, et al. 2014	Melt pool like shape	Pyrometry	porosity	mapping	[350]

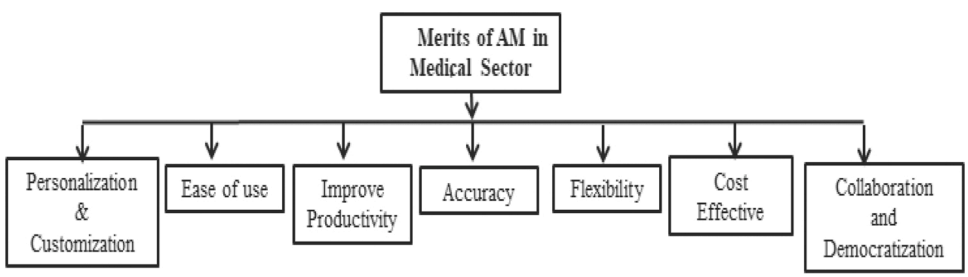

Fig. 22. Merits of additive manufacturing in medical applications [351].

5. Summary

Although additive manufacturing has lot of advantages (Innovation, creation of complex shape, less waste, cheaper for small batch production, single step operation, less wait age time, customization and high flexibility) over traditional manufacturing, but still it has some limitations (Poor mechanical properties and limited materials availability, high cost for large volume production etc.). Hence it is important to mention the comparison of additive manufacturing with conventional manufacturing processes. So, that futuristic researcher can overcome the challenges of additive manufacturing processes. The estimation cost of additive manufacturing and conventional manufacturing is depicted in Tables 12a–12c.

6. Conclusions

Additive manufacturing is an effective, novel, revolutionizing and rapidly growing technology especially in medical sector. Recently, AM technology represents a large opportunity to help pharmaceutical as well as medical companies to generate more specific drugs and changing the way that surgeons and doctors plan procedures, customization with high accuracy. The four major core applications of AM in medical field that are associated with recent innovations are: bio printing tissues and organoids, patient-specific surgical models, surgical tools, and custom-made prosthetics. Recently, AM providing distinct possibilities for application in medicine such as in craniofacial implants to hip, knee and spinal implants, prosthetic dentistry, production of various medical tools used for cutting and drilling in surgery etc. A comprehensive literature review has been performed to study the mechanical properties of different additive manufacturing processes with different materials and their biomedical applications. This study also highlights the future challenges and application of additive manufacturing in biomedical field.

7. Future challenges

Additive manufacturing technology plays an important role especially in medical applications. But, some more applications such as organ printing is still need to research. Although, AM provides number of advantages to manufacturers such as cost savings and optimization of product design, shorter supply chain, customization, ability to produce complex geometry, etc. Over the last decade, additive manufacturing growing rapidly in the medical sector, however, there are still some challenges in adopting 3D printing. The some important challenges that facing the manufacturer are as follow.

(a) ***Limited choice of materials***: The raw materials source for the

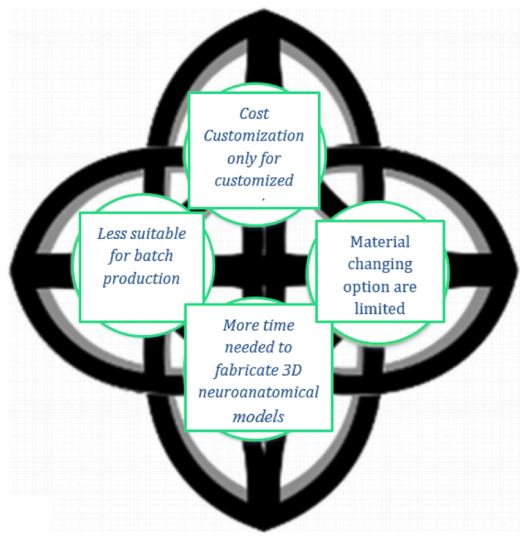

Fig. 23. Demerits of additive manufacturing in medical applications.

Table 12a
Estimation cost of raw material in conventional method [374].

Item/Material	Production of items in sets	No. of piece required and Quantity	Approx. cost for single item in%age
Tubes (Stainless steel 304 L)	20	2 (Small)	0.95
Tubes (Stainless steel 304 L)	60	2 (large)	1.10
Plate or Billet (Stainless steel 304 L)	20	Small	3.81
Plate or Billet (Stainless steel 304 L)	60	Large	4.40

Table 12b
Estimation of process cost in conventional method [374].

Item/Part	Process	Production of items in sets	Quantity	Machine	Approx. cost for single item in%age
Blower head	Machining	20	Small	4 axis CNC	80.95
Blower head	Machining	60	Large	4 axis CNC	82.41
Duct	Fabrication	60	Large	Turning	4.40
Duct	Fabrication	20	Small	Turning	4.76

Table 12c
Cost model elements, DMLS pathway [374].

S.No.	Cost model element	Value
1	Machine purchase	€ 411048.68
2	Annual operating hours	5000 h
3	Maintenance costs	€ 24854.11 per year
4	Energy price	€ 0.02 / MJ
5	Process energy consumption rate	9.18 MJ / h
6	Energy price	€ 0.02 / MJ

fabrication of suitable or similar part/object to human organs & tissues are limited.

***(b)* Poor mechanical properties**: The part should have reasonable mechanical characteristics such as compress strength, tensile etc. after printing process.

(3) ***Low dimensional accuracy*:** The component fitting is very essential for a highly precise design; the barrier is to overcome the shrinkage of the component during the process of cooling.

***(4)*. Customization of fit & design**: As the part is fabricated to the patient function, shape or size, it cannot be utilized in other patients.

In addition, the other challenges of additive manufacturing include high cost of printer, not suitable for mass production, post-processing requirements, speed of bio printer. Hence more research is required on 3D printing material, process technique and applications of additive manufacturing.

Declaration of Competing Interest

The authors report no declarations of interest.

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