International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 07 Issue: 07 | July - 2023 SJIF Rating: 8.176 ISSN: 2582-3930

Recent Advancements in 3-D Printing in Medical Applications

1st Aarti Singh
Department of Mechanical Engineering
Ajay Kumar Garg Engineering College
Ghaziabad, Uttar Pradesh-201009, India
aartisingh06072001@gmail.com

2nd Tarun Bhardwaj
Department of Mechanical Engineering
Ajay Kumar Garg Engineering College
Ghaziabad, Uttar Pradesh-201009, India
bhardwajtarun@akgec.ac.in

3rd Puneet Saini
Department of Mechanical Engineering
Ajay Kumar Garg Engineering College
Ghaziabad, Uttar Pradesh-201009, India
sainipuneet@akgec.ac.in

4th Namrata Gangil
Department of Mechanical Engineering
Ajay Kumar Garg Engineering College
Ghaziabad, Uttar Pradesh-201009, India
guptanamrata@akgec.ac.in

5th Dinesh Kumar Singh
Department of Mechanical Engineering
Ajay Kumar Garg Engineering College
Ghaziabad, Uttar Pradesh-201009, India
singhdk@akgec.ac.in

6th Vijay Kumar
Department of Pharmaceutics,
School of Pharmaceutical Education & Research (SPER),
Jamia Hamdard,
New Delhi-110062, India
vijaypharma1997@gmail.com

Abstract:
The field of three-dimensional (3D) printing has witnessed significant advancements in recent years, and its potential for revolutionizing medical applications is rapidly emerging. This review aims to provide an overview of the current state and scope of 3D printing in the medical field. The review begins by highlighting the various 3D printing technologies currently employed in healthcare settings, including stereolithography, selective laser sintering, fused deposition modeling, and inkjet printing. Each technology's advantages and limitations are discussed, shedding light on their suitability for different medical applications. Next, the review delves into the diverse range of medical applications where 3D printing has shown promise. These applications include the fabrication of patient-specific anatomical models for preoperative planning, surgical guides and tools, customized implants and prosthetics, tissue engineering scaffolds, and drug delivery systems. The potential benefits of using 3D printing in these areas, such as enhanced surgical accuracy, improved patient outcomes, reduced surgery time, and personalized medicine, are explored. Furthermore, the review addresses the challenges and limitations associated with implementing 3D printing in medical settings. These challenges include regulatory concerns, standardization of processes, material biocompatibility, cost-effectiveness, and scalability. The ongoing efforts to overcome these barriers and the future directions of 3D printing in medicine are also discussed. In conclusion, 3D printing holds immense potential for transforming various aspects of medical practice. While considerable progress has been made, there are still challenges to be addressed before widespread adoption can be achieved. With continued research and development, coupled with regulatory support and collaboration between academia, industry, and healthcare professionals, 3D printing is poised to

make a substantial impact in the field of medicine, improving patient care and treatment outcomes.

Key words:
Additive manufacturing (AM); Bio-medical; Fused Deposition Modelling (FDM); Selective Laser Sintering (SLS); Stereolithography (SLA); Digital Light Processing (DLP); Binder Jetting; Material Jetting; Direct Energy Deposition (DED).

1. INTRODUCTION

3D printing, also known as additive manufacturing, has emerged as a transformative technology in various fields, including the medical industry. Its unique ability to create complex three-dimensional structures layer by layer has opened up new possibilities for medical applications. In this current review, the scope of 3D printing in medical applications and its impact on patient care, research, and education is explored [1].

1.1. Patient-Specific Implants and Prosthetics: One of the most significant applications of 3D printing in medicine is the production of patient-specific implants and prosthetics. By utilizing patient scans, such as CT or MRI, medical professionals can create customized implants that perfectly fit the anatomy of individual patients. This not only improves the functionality and comfort of the implants but also reduces surgical complications and recovery time [2].

1.2. Surgical Guides and Instrumentation: 3D printing enables the creation of surgical guides and instrumentation tailored to specific surgical procedures. Surgeons can design and produce patient-specific guides that assist in precise surgical interventions, reducing the risk of errors and enhancing surgical outcomes. Additionally, complex surgical instruments can be 3D printed, allowing for improved ergonomics and better surgical performance [3], [4].

1.3. Tissue and Organ Engineering: Another exciting area where 3D printing holds immense potential is tissue and organ engineering. By using specialized 3D printers that can deposit living cells, scientists are working towards developing functional tissues and even complete organs. This technology has the potential to revolutionize organ transplantation by eliminating long waiting lists and reducing the risk of organ rejection [5], [6].

1.4. Bio printing and Drug Testing: 3D printing plays a crucial role in bio printing, which involves the fabrication of complex three-dimensional structures using living cells. Researchers can create realistic tissue models for drug testing and screening, reducing the reliance on animal models and improving the efficiency and accuracy of preclinical studies [7], [8].

1.5. Medical Education and Training: 3D printing has significantly impacted medical education and training. It allows for the production of anatomical models that accurately replicate patient anatomy, enabling medical students and healthcare professionals to practice surgical procedures and gain hands-on experience before entering the operating room. These models can also be used to educate patients about their conditions and treatment plans [9].

1.6. Customized Drug Delivery Systems: 3D printing has the potential to revolutionize drug delivery systems by enabling the fabrication of personalized dosage forms. This technology can be used to create patient-specific drug formulations with precise dosages, shapes, and release profiles, improving treatment outcomes and patient adherence [10].

1.7. Prosthetic and Orthotic Devices: 3D printing offers a cost-effective and efficient method for producing prosthetic and orthotic devices. By leveraging 3D scanning technology and computer-aided design, custom-fit devices can be created, improving comfort and functionality for individuals with limb differences or musculoskeletal disorders [11].

1.8. Surgical Simulation and Preoperative Planning: Surgeons can use 3D printing to create patient-specific anatomical models, allowing for detailed preoperative planning and simulation. This technology enhances surgical precision, reduces operative time, and minimizes the risk of complications [12].

The scope of 3D printing in medical applications is vast and continually expanding. It has the potential to revolutionize patient care, research, and education by enabling patient-specific treatments, improving surgical outcomes, advancing tissue engineering, and enhancing medical training. As 3D printing technology continues to evolve, it holds promise for further advancements in the field of medicine [12], [13].

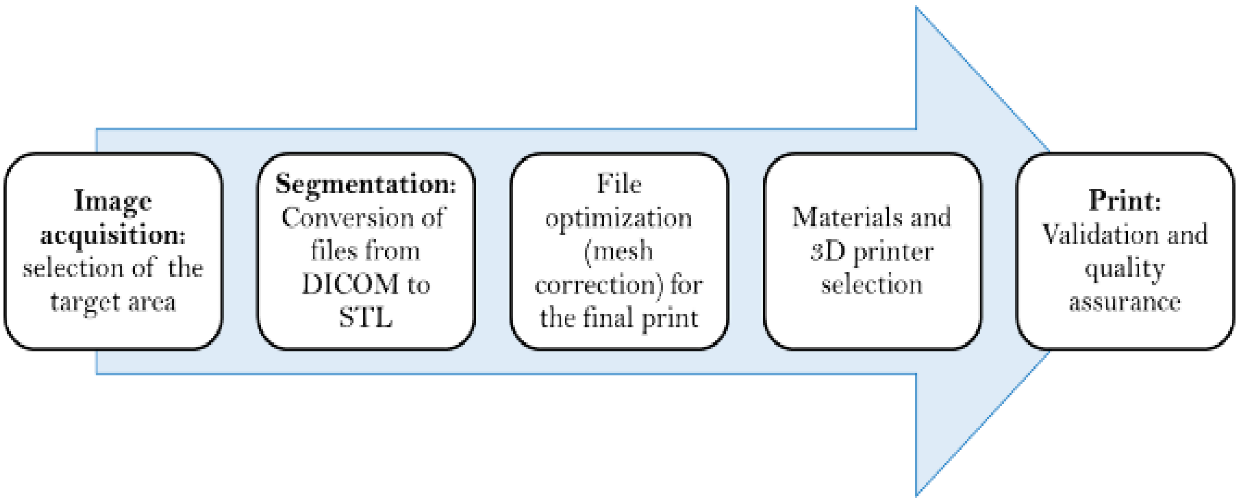


Fig. 1: 3D-printing workflow.

2. ADDITIVE MANUFACTURING TECHNOLOGIES

Additive manufacturing, also known as 3D printing, refers to the process of creating three-dimensional objects by adding successive layers of material. It is a rapidly evolving field with various technologies and techniques [14], [15]. Here are some of the commonly used additive manufacturing technologies:

2.1 Fused Deposition Modeling (FDM): FDM is one of the most widely used 3D printing technologies. It works by extruding thermoplastic materials, such as ABS or PLA, through a heated nozzle. The material is deposited layer by layer to create the desired object [16].

2.2 Stereolithography (SLA): SLA uses a vat of liquid photopolymer resin and a UV laser to selectively solidify the resin layer by layer. The object is built upside-down, with each layer being cured by the laser. SLA is known for its high level of detail and surface finish [17].

2.3 Selective Laser Sintering (SLS): SLS employs a high-power laser to selectively fuse powdered materials, such as nylon or metal, layer by layer. The unused powder acts as a support structure during the printing process, eliminating the need for additional supports [18].

2.4 Digital Light Processing (DLP): DLP is similar to SLA but uses a digital light projector to cure the entire layer of resin simultaneously. The projector displays a single image of each layer, solidifying the resin all at once. DLP offers faster printing speeds compared to SLA [19], [20].

2.5 Binder Jetting: In binder jetting, a liquid binding agent is selectively deposited onto layers of powdered material, such as metal or sand. The binder binds the particles together, and additional layers are added until the object is fully formed. The final part is then cured or sintered to achieve its desired strength [21].

2.6 Material Jetting: Material jetting operates similarly to inkjet printing. It uses print heads to deposit droplets of liquid photopolymer onto a build platform. Each layer is cured using UV light, and the process is repeated until the object is complete. Material jetting can produce multi-material and full-color objects [22].

2.7 Direct Energy Deposition (DED): DED involves the use of a nozzle that deposits molten material. Typically metal, onto a substrate or previously printed layers. The material is rapidly solidified to form the desired shape. D&D is commonly used in the production of large-scale metal parts and repairs [23].

These are just a few examples of additive manufacturing technologies. Each technology has its strengths and limitations, making them suitable for different applications and industries. The field of additive manufacturing continues to advance, with ongoing research and development efforts focused on improving speed, resolution, material selection and scalability.

3. TRANSFORMATION PROCESS AND MATERIALS USED

The transformation process refers to the series of steps or operations that are carried out to convert raw materials or inputs into finished products or outputs. It involves various stages, including material selection, design, manufacturing, assembly, and quality control [24]–[26].

The specific transformation process and materials used can vary greatly depending on the product being manufactured and the industry involved. However, I can provide a general overview of some common transformation processes and materials used in different industries:

3.1 Manufacturing Industry:

- Casting: Involves pouring molten metal or liquid material into a mold to create a solid shape. Materials used can include metals such as iron, aluminum, and steel, as well as non-metallic materials like plastic.
- Machining: Utilizes cutting tools to remove material from a work-piece and shape it into the desired form. Commonly machined materials include metal alloys, plastics, and composites.
- Welding: Joins two or more pieces of metal or thermoplastics together using heat or pressure. Welding processes involve materials such as steel, aluminum, copper, and various alloys.
- Injection Molding: Used for mass production of plastic parts by injecting molten plastic into a mold. Thermoplastics like polyethylene, polypropylene, and polystyrene are commonly used.
- 3D Printing/Additive Manufacturing: Builds objects layer by layer using computer-controlled processes. Materials used can include plastics, metals, ceramics, and even biological materials [27]–[29].

3.2 Construction Industry:

- Concrete Mixing: Involves combining cement, aggregates (such as sand and gravel), water, and sometimes additives to create concrete, a widely used construction material.
- Steel Fabrication: Involves cutting, shaping, and assembling steel components to create structures like beams, columns, and frames.
- Woodworking: Utilizes various types of wood, such as hardwood and softwood, to create structures, furniture, and decorative elements [30]–[32].

3.3 Textile Industry:

- Spinning: Converts raw fibers (such as cotton, wool, or synthetic fibers) into yarns through twisting and stretching processes.
- Weaving/Knitting: Interlaces yarns to create fabrics. Materials used can include cotton, silk, wool, polyester, and blends of different fibers.
- Dyeing/Printing: Applies color or patterns to textiles using dyes or printing techniques [33], [34].

3.4 Food Industry:

- Processing: Involves transforming raw food materials through cleaning, sorting, cutting, cooking, and packaging processes. Materials used can include various fruits, vegetables, grains, meat, and dairy products [35], [36].

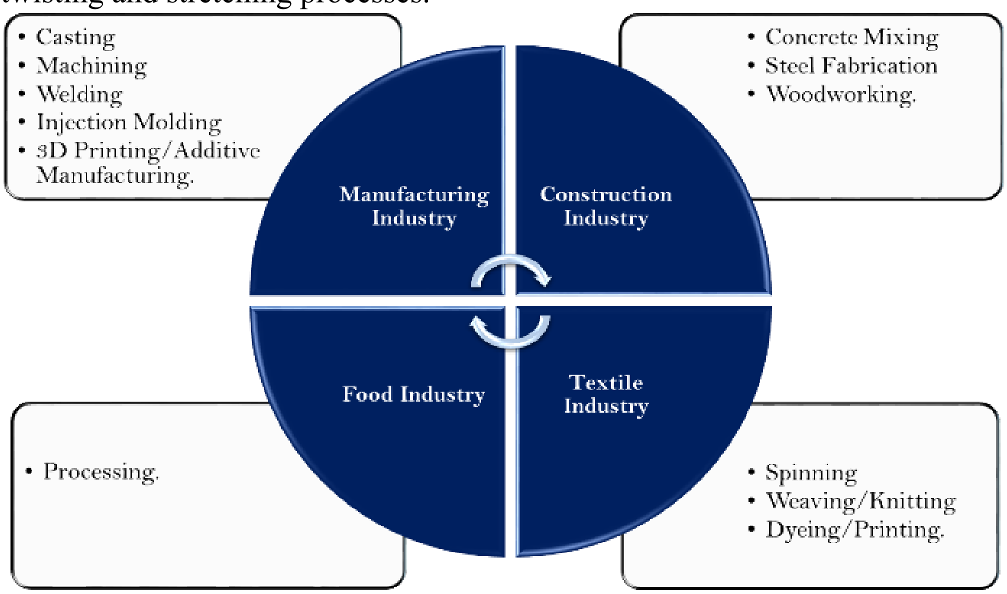


Fig. 2: Schematic process of Transformation and Materials.

These are just a few examples of transformation processes and materials used in different industries. Each industry and product will have its own specific requirements and processes tailored to meet those needs [37].

4. ROLE OF 3D PRINTING IN MEDICAL FIELD

3D printing, also known as additive manufacturing, has numerous applications in the medical field [38], [39]. Here are some of the roles of 3D printing in the medical field:

4.1. **Customized Prosthetics and Implants:** 3D printing can be used to create customized prosthetics and implants that fit a patient's unique anatomy perfectly. This can help improve patient outcomes and reduce the need for revision surgery [40], [41].

4.2. **Surgical Planning:** 3D printing can be used to create anatomically accurate models of a patient's organs or body part which can be used to plan surgical procedures more accurately and reduce the risks and mistakes during surgery [42].

4.3. **Medical Education and Training:** Medical students and surgical residents can use 3D printed models to practice and prepare for surgeries, leading to improved understanding of anatomy and better clinical outcomes [43], [44].

4.4. **Drug Delivery:** 3D printing can produce customized drug-delivery systems that are tailored to individual patient needs, ensuring the correct medication doses and the proper targeting of specific areas of the body [45], [46].

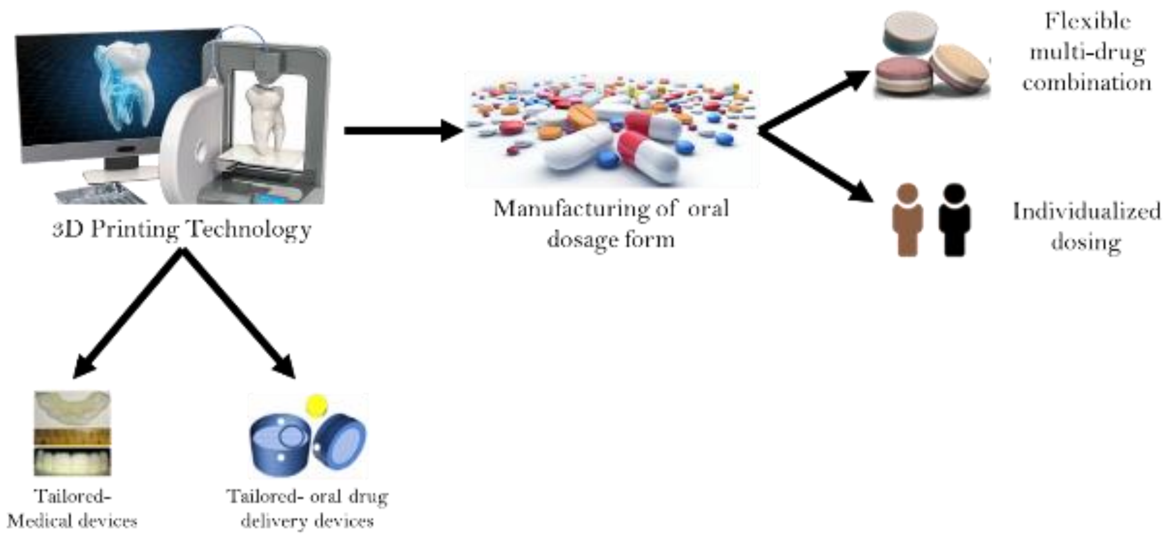
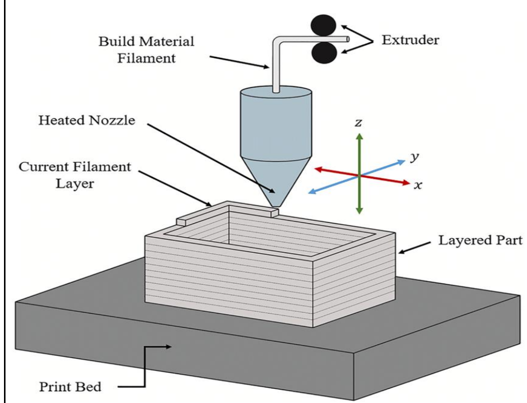
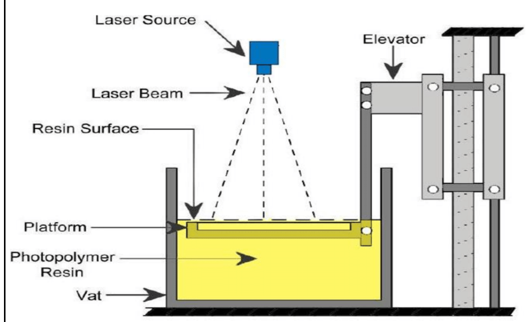


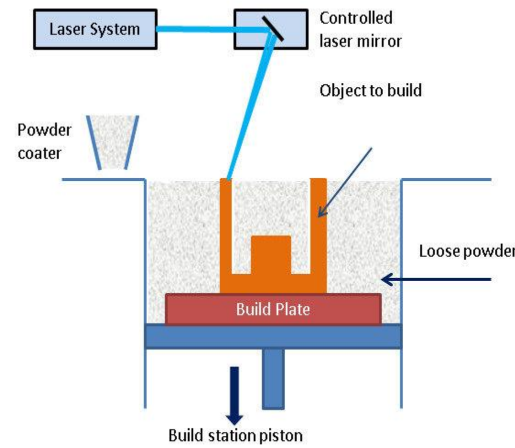
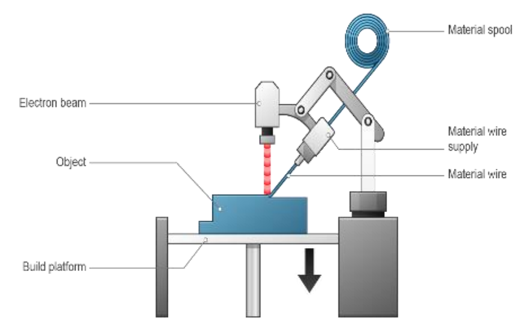
Fig. 3: Oral drug delivery system for 3D printing.

4.5. **Tissue Engineering:** 3D printing is used by researchers to create biomimetic structures for tissue engineering and regenerative medicine. 3D printed organs, tissues, and scaffolds can be used for transplantation instead of relying on organ donations [47], [48].

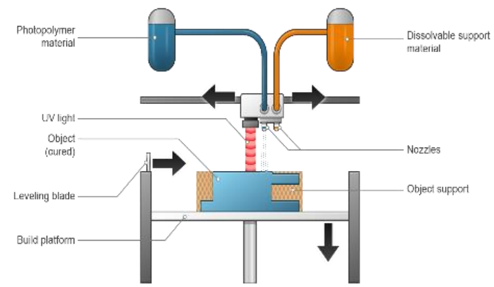
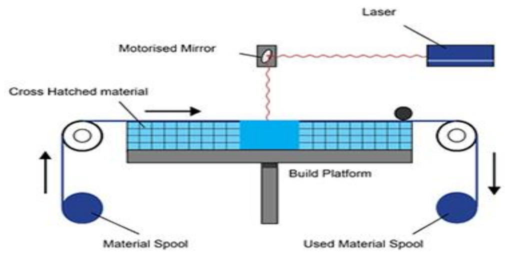
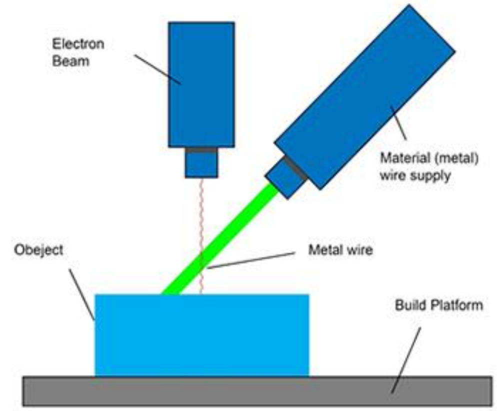
International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 07 Issue: 07 | July - 2023 SJIF Rating: 8.176 ISSN: 2582-3930

Table 1: Summary of 3D-printing process and techniques, focusing on essential materials and medical applications, and comparison between 3D-printing techniques:

S. No.	Technologies	Materials	Medical uses	Advantages	Limitations	Schematic Diagram	Reference
1.	Fused Deposition Modeling (FDM)	a) Plastics; b) Polymer: ABS, Nylon, PC, AB	Medical devices and equipment, rapid prototyping exoskeleton	a) Cheap process, b) Comprehensive, c) ABS Plastic Backed: Good structural features and easily accessible.	a) Dependence of quality on nozzle radius: Large nozzle leads to poor quality, b) Low accuracy and dependence on nozzle thickness, c) Low speed, d) Contact pressure required to increase quality.		[49]-[51]
2.	Stereo lithography (SLA)	a) Photopolymer resin	bone, dental models, dental implant guides, hearing aids	a) High resolution and accuracy, b) Complex parts, c) Good surface finish: smooth finish, d) Flexible printing setup.	a) Loss of strength and durability, b) Affected by UV light even after print, c) Not for heavy use.		[52]-[54]

3.	Selective laser sintering (SLS)	a) SHS: Nylon; b) DMLS, SLS, SLM: Stainless Steel, Titanium, Aluminium, Cobalt Chrome, Steel; c) EBM: Titanium, Cobalt Chrome, Stainless Steel Material, Aluminum and copper.	models that require a mesh, medical devices such as implants and fixation	a) Affordable, b) Small technology: office size machine, c) Large range of material options.	a) Low speed; lack of structural properties in materials, b) limited size, c) Dependence on grain size of the powder.		[55]-[56]
4.	Binder jetting	a) Stainless Steel b) Polymer: ABS, PA, PC c) Ceramic: Glass	Color model specifically color coding of anatomy	a) Range of colors, b) many materials supported, c) fast, d) Different binder-powder combinations for different mechanical properties.	a) Not always suitable for structural parts, b) Cleaning 3D-printing results in time consuming and increases process time.		[57]–[59]

International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 07 Issue: 07 | July - 2023 SJIF Rating: 8.176 ISSN: 2582-3930

5.	Material jetting	a) Plastic b) Polymer: Polypropylene, HDPE, PS, PMMA, PC, ABS, HIPS, EDP	medical model, dental cast, dental implant guide	a) High accuracy, b) Less wastage of material, c) Multiple material parts and colors in one process.	a) Necessary auxiliary material, b) Limited material: Only polymers and waxes are supported.		[60]–[63]
6.	Laminated object manufacturing (LOM)	Paper, plastic and metal sheets	Orthopedic Modeling of Bone Surfaces	a) Speed, b) Cheap, c) Ease of material handling.	a) Dependence on paper or plastic material, b) Requirement of post processing, c) Limited material range.		[64]-[66]
7.	Direct energy deposition (DED)	Metals: Cobalt Chrome, Titanium	Limited. Commonly used for repair of existing parts and manufacture of very large parts	a) high control of grain structure, b) high-quality-speed dependent, c) high-precision-accuracy dependent, d) rapidly manufactured with rapid material deposition, e) fully dense parts; no need for supports, f) Best practice for repairing parts.	a) Limited range of materials, b) Poor surface quality, c) Wire process is less accurate.		[67], [68]

Overall, 3D printing is proving to be a revolutionary technology for the medical field, contributing to improving medical treatments, reducing surgery time, and training professionals in the field.

4.6. Lack of Regulation:

The lack of regulation in the 3D printing field could potentially pose some concerns, especially in medical applications [69], [70]. Here are some of the scope and risks associated with it:

4.6.1. Quality and accuracy control: The accuracy of 3D printed medical devices and implants needs to be highly precise, as even minor deviations could cause significant harm to the patients. Without proper regulation, there is a risk that quality control may not be adequate to ensure the safety and efficacy of 3D printed medical products [71].

4.6.2. Material Selection: The materials used in 3D printing should be biocompatible and meet rigorous safety standards. The lack of regulation can lead to the use of untested or potentially harmful materials, increasing the risk of patient complications [72], [73].

4.6.3. Intellectual Property Concerns: 3D printing is open-source and accessible to everyone, making it difficult to regulate the use of intellectual property and patents. It could lead to the creation of counterfeit medical devices, which may not be safe or effective [74].

4.6.4. Privacy and Data Security: 3D printing in the medical field requires access to sensitive patient data, which needs to be stored and secured appropriately. Without proper regulation, there is a risk of data breaches or cyber-attacks, which could endanger patient privacy and security [75], [76].

In conclusion, 3D printing is an innovative technology with significant potential for medical applications, but it requires proper regulation to ensure patient safety and effectiveness. As the use of 3D printing in the medical field continues to grow, it is essential to establish clear standards and guidelines to mitigate the risks associated with it.

4.7. Examples of Application of 3D Printing in Paediatric Cases:

4.7.1. Customized Prosthetics: Children with limb deficiencies or amputations can benefit from 3D printing to create a customized prosthetic that is tailored to their needs. These prosthetics can be designed to be lightweight, comfortable, and cost-effective compared to traditional prosthetics [41].

4.7.2. Surgical Planning and Practice: 3D printing allows doctors to have an accurate replica of a patient's anatomy. Using 3D printed models, doctors can plan surgeries and practice difficult procedures, reducing the risk of complications and increasing the chances of success [77], [78].

4.7.3. Medical Training: 3D printing can be used to create models of organs and other body parts. These models can be used to train medical professionals in the anatomy of developing bodies, which can be particularly helpful in paediatric cases as it provides valuable insights into the differences between adult and child anatomy [79].

4.7.4. Orthodontics: 3D printing assists in creating customized orthodontic appliances such as dental aligners, braces, and retainers that can fit better for the specific patient [80].

4.7.5. Hearing Aids: 3D printing can be used to create customized hearing aids for children. The hearing aids can be made using a digital scan of the patient's ear to produce a comfortable and individual fit [81], [82].

4.7.6. Surgical Instruments: 3D printing can be used to create surgical instruments for paediatric procedures. 3D printing can assist in creating miniature surgical instruments, dental tools, and devices with intricate shapes, making surgeries easier to perform [83], [84].

In conclusion, 3D printing can play a vital role in paediatric care, from prosthetics to surgical planning and training medical professionals. 3D printing has shown to make medical care more accessible, efficient, and customized, thus opening a horizon of new possibilities.

5. CONCLUSION

The 3-D printing technology in medical applications and healthcare industry demonstrates its significant potential and impact. 3D printing has emerged as a promising tool for creating patient-specific anatomical models, surgical guides, implants, prosthetics, and even functional organs. Its ability to produce complex, customized structures with precision and accuracy has revolutionized various aspects of medical practice.

The Integration of 3D printing has facilitated enhanced surgical planning, allowing surgeons to visualize and simulate procedures before performing them. This technology has also contributed to better patient outcomes by enabling the creation of personalized medical devices and implants that perfectly fit the individual's unique anatomy. Additionally, 3D-printed models have proved valuable in medical education, enabling hands-on training and improving surgical skills.

Despite the numerous advancements and successes, there are still challenges and limitations to be addressed. The high cost of 3D printing equipment, materials, and regulatory issues pose barriers to widespread adoption. Further research is required to optimize materials used in 3D printing for medical applications, ensuring their safety, biocompatibility, and durability. Additionally, the scalability and production speed of 3D-printed medical devices and organs need to be improved to meet the demands of the healthcare industry.

3D printing holds tremendous potential in medical applications and has already made significant strides in transforming healthcare. With continued research, technological advancements, and cost reductions, 3D printing is poised to become an indispensable tool in various medical specialties, revolutionizing patient care, surgical procedures, and personalized medicine.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

FUNDING

Nil

REFERENCES

[1] M. Jiménez, L. Romero, I. A. Domínguez, M. D. M. Espinosa, and M. Domínguez, "Additive Manufacturing Technologies: An Overview about 3D Printing Methods and Future Prospects," *Complexity*, 2019, doi: 10.1155/2019/9656938.

[2] D. Kumar Gupta *et al.*, "3D printing technology in healthcare: applications, regulatory understanding, IP repository and clinical trial status," *Journal of Drug Targeting*. 2022. doi: 10.1080/1061186X.2021.1935973.

[3] D. Hoang, D. Perrault, M. Stevanovic, and A. Ghiassi, "Today surgical applications of three-dimensional printing: A review of the current literature & how to get started," *Annals of Translational Medicine*, 2016, doi: 10.21037/atm.2016.12.18.

[4] M. L. Sun, Y. Zhang, Y. Peng, D. J. Fu, H. Q. Fan, and R. He, "Accuracy of a Novel 3D-Printed Patient-Specific Intramedullary Guide to Control Femoral Component Rotation in Total Knee Arthroplasty," *Orthopaedic surgery*, 2020, doi:

10.1111/os.12619.

[5] X. Wang *et al.*, "3D bioprinting technologies for hard tissue and organ engineering," *Materials*. 2016. doi: 10.3390/ma9100802.

[6] V. Mironov, T. Boland, T. Trusk, G. Forgacs, and R. R. Markwald, "Organ printing: Computer-aided jet-based 3D tissue engineering," *Trends in Biotechnology*, 2003, doi: 10.1016/S0167-7799(03)00033-7.

[7] R. Durga Prasad Reddy and V. Sharma, "Additive manufacturing in drug delivery applications: A review," *International Journal of Pharmaceutics*, 2020, doi: 10.1016/j.ijpharm.2020.119820.

[8] G. Pennarossa, S. Arcuri, T. De Iorio, F. Gandolfi, and T. A. L. Brevini, "Current advances in 3D tissue and organ reconstruction," *International Journal of Molecular Sciences*, 2021, doi: 10.3390/ijms22020830.

[9] E. K. O'Brien, D. B. Wayne, K. A. Barsness, W. C. McGaghie, and J. H. Barsuk, "Use of 3D Printing for Medical Education Models in Transplantation Medicine: a Critical Review," *Current Transplantation Reports*, 2016, doi: 10.1007/s40472-016-0088-7.

[10] J. Goole and K. Amighi, "3D printing in pharmaceutics: A new tool for designing customized drug delivery systems," *International Journal of Pharmaceutics*. 2016. doi: 10.1016/j.ijpharm.2015.12.071.

[11] A. Sirinterlikci and I. Swink, "3D-printing orthotic and prosthetic devices," *Manufacturing Engineering*, 2015.

[12] W. Cho, A. V. Job, J. Chen, and J. H. Baek, "A review of current clinical applications of three- dimensional printing in spine surgery," *Asian Spine Journal*. 2018. doi: 10.4184/asj.2018.12.1.171.

[13] I. Lau and Z. Sun, "Three-dimensional printing in congenital heart disease: A systematic review," *Journal of Medical Radiation Sciences*. 2018. doi: 10.1002/jmrs.268.

[14] S. Rossi, A. Puglisi, and M. Benaglia, "Additive Manufacturing Technologies: 3D Printing in Organic Synthesis," *ChemCatChem*. 2018. doi: 10.1002/cctc.201701619.

[15] L. Jyothish Kumar, P. M. Pandey, and D. I. Wimpenny, *3D printing and additive manufacturing technologies*. 2018. doi: 10.1007/978-981-13-0305-0.

[16] M. R. P. Araújo, L. L. Sa-Barreto, T. Gratieri, G. M. Gelfuso, and M. Cunha-Filho, "The digital pharmacies era: How 3D printing technology using fused deposition modeling can become a reality," *Pharmaceutics*. 2019. doi: 10.3390/pharmaceutics11030128.

[17] G. Ding, R. He, K. Zhang, N. Zhou, and H. Xu, "Stereolithography 3D printing of SiC ceramic with potential for lightweight optical mirror," *Ceramics International*, 2020, doi: 10.1016/j.ceramint.2020.04.196.

[18] N. Allahham *et al.*, "Selective laser sintering 3D printing of orally disintegrating printlets containing ondansetron," *Pharmaceutics*, 2020, doi: 10.3390/pharmaceutics12020110.

[19] X. Kuang *et al.*, "Grayscale digital light processing 3D printing for highly functionally graded materials," *Science Advances*, 2019, doi: 10.1126/sciadv.aav5790.

[20] H. Hwangbo and S. J. Jeon, "Digital light processing 3D printing of multi-materials with improved adhesion using resins containing low functional acrylates," *Korean Journal of Chemical Engineering*, 2022, doi: 10.1007/s11814-021-0934-x.

[21] N. Lecis, R. Beltrami, and M. Mariani,

"Binder jetting 3D printing of 316 stainless steel: Influence of process parameters on microstructural and mechanical properties," *Metallurgia Italiana*, 2021.

[22] A. Bournias Varotsis, "Introduction to Material Jetting 3D Printing," *HUBS: a protolabs Company*, 2019.

[23] D. J. Ryu *et al.*, "Titanium porous coating using 3D direct energy deposition (DED) printing for cementless TKA implants: Does it induce chronic inflammation?," *Materials*, 2020, doi: 10.3390/ma13020472.

[24] Q. Zhang, D. Yan, K. Zhang, and G. Hu, "Pattern Transformation of Heat-Shrinkable Polymer by Three-Dimensional (3D) Printing Technique," *Scientific Reports*, 2015, doi: 10.1038/srep08936.

[25] A. Bagheri, C. M. Fellows, and C. Boyer, "Reversible Deactivation Radical Polymerization: From Polymer Network Synthesis to 3D Printing," *Advanced Science*. 2021. doi: 10.1002/advs.202003701.

[26] K. Faksawat, P. Limsuwan, and K. Naemchanthara, "3D printing technique of specific bone shape based on raw clay using hydroxyapatite as an additive material," *Applied Clay Science*, 2021, doi: 10.1016/j.clay.2021.106269.

[27] G. Prashar, H. Vasudev, and D. Bhuddhi, "Additive manufacturing: expanding 3D printing horizon in industry 4.0," *International Journal on Interactive Design and Manufacturing*, 2022, doi: 10.1007/s12008-022-00956-4.

[28] J. Prinsloo, S. Sinha, and B. von Solms, "A review of industry 4.0 manufacturing process security risks," *Applied Sciences (Switzerland)*. 2019. doi: 10.3390/app9235105.

[29] J. Cui, L. Ren, J. Mai, P. Zheng, and L. Zhang, "3D Printing in the Context of Cloud Manufacturing," *Robotics and Computer-Integrated Manufacturing*, 2022, doi: 10.1016/j.rcim.2021.102256.

[30] Y. W. D. Tay, B. Panda, S. C. Paul, N. A. Noor Mohamed, M. J. Tan, and K. F. Leong, "3D printing trends in building and construction industry: a review," *Virtual and Physical Prototyping*. 2017. doi: 10.1080/17452759.2017.1326724.

[31] İ. E. Öztürk and G. B. Öztürk, "The Future of 3D Printing Technology in the Construction Industry: a Systematic Literature Review," *Eurasian Journal of Civil Engineering and Architecture*, 2018.

[32] B. T. Program and C. Author, "The Future of 3D Printing Technology in the Construction Industry: a Systematic Literature Review," *Eurasian Journal of Civil Engineering and Architecture*, 2018.

[33] D. B. Sitotaw, D. Ahrendt, Y. Kyosev, and A. K. Kabish, "Additive manufacturing and textiles-state-of-the-art," *Applied Sciences (Switzerland)*. 2020. doi: 10.3390/app10155033.

[34] M. C. Biswas, "Fused Deposition Modeling 3D Printing Technology in Textile and Fashion Industry: Materials and Innovation," *Modern Concepts in Material Science*, 2019, doi: 10.33552/mcms.2019.02.000529.

[35] J. Lee, "A 3d food printing process for the new normal era: A review," *Processes*. 2021. doi: 10.3390/pr9091495.

[36] T. Pereira, S. Barroso, and M. M. Gil, "Food texture design by 3d printing: A review," *Foods*. 2021. doi: 10.3390/foods10020320.

[37] M. G. Bedoya, D. R. Montoya, G. Tabilo-Munizaga, M. Pérez-Won, and R. Lemus-Mondaca, "Promising perspectives on novel protein food sources combining artificial

intelligence and 3D food printing for food industry," *Trends in Food Science and Technology*. 2022. doi: 10.1016/j.tifs.2022.05.013.

[38] I. Tasneem, A. Ariz, D. Bharti, A. Haleem, M. Javaid, and S. Bahl, "3D Printing Technology and its Significant Applications in the Context of Healthcare Education," *Journal of Industrial Integration and Management*, 2021, doi: 10.1142/S2424862221500159.

[39] D. S. C. Soon, M. P. Chae, C. H. C. Pilgrim, W. M. Rozen, R. T. Spychal, and D. J. Hunter-Smith, "3D haptic modelling for preoperative planning of hepatic resection: A systematic review," *Annals of Medicine and Surgery*. 2016. doi: 10.1016/j.amsu.2016.07.002.

[40] J. K. S. Tsui, S. Bell, L. da Cruz, A. D. Dick, and M. S. Sagoo, "Applications of three-dimensional printing in ophthalmology," *Survey of Ophthalmology*. 2022. doi: 10.1016/j.survophthal.2022.01.004.

[41] M. J. Mirzaali, V. Moosabeiki, S. M. Rajaai, J. Zhou, and A. A. Zadpoor, "Additive Manufacturing of Biomaterials—Design Principles and Their Implementation," *Materials*, vol. 15, no. 15, 2022, doi: 10.3390/ma15155457.

[42] Y. H. Huang, R. Seelaus, L. Zhao, P. K. Patel, and M. Cohen, "Virtual surgical planning and 3D printing in prosthetic orbital reconstruction with percutaneous implants: A technical case report," *International Medical Case Reports Journal*, 2016, doi: 10.2147/IMCRJ.S118139.

[43] J. Meyer-Szary *et al.*, "The Role of 3D Printing in Planning ComplexMedical Procedures and Training of Medical Professionals—Cross-Sectional Multispecialty Review," *International Journal of Environmental Research and Public Health*, 2022, doi: 10.3390/ijerph19063331.

[44] A. H. Bati, "3D modelling for realistic training and learning," *Turkish Journal of Biochemistry*, 2022, doi: 10.1515/tjb-2019-0182.

[45] Afsana, V. Jain, N. Haider, and K. Jain, "3D Printing in Personalized Drug Delivery," *Current Pharmaceutical Design*, 2019, doi: 10.2174/1381612825666190215122208.

[46] K. Tappa *et al.*, "3D printing custom bioactive and absorbable surgical screws, pins, and bone plates for localized drug delivery," *Journal of Functional Biomaterials*, 2019, doi: 10.3390/jfb10020017.

[47] C. Wang *et al.*, "3D printing of bone tissue engineering scaffolds," *Bioactive Materials*. 2020. doi: 10.1016/j.bioactmat.2020.01.004.

[48] A. Zaszczyńska, M. Moczulska-Heljak, A. Gradys, and P. Sajkiewicz, "Advances in 3D printing for tissue engineering," *Materials*. 2021. doi: 10.3390/ma14123149.

[49] A. Aimar, A. Palermo, and B. Innocenti, "The Role of 3D Printing in Medical Applications: A State of the Art," *Journal of Healthcare Engineering*. 2019. doi: 10.1155/2019/5340616.

[50] G. H. Loh, E. Pei, J. Gonzalez-Gutierrez, and M. Monzón, "An overview of material extrusion troubleshooting," *Applied Sciences (Switzerland)*. 2020. doi: 10.3390/app10144776.

[51] "Extruder Selection, Design, and Operation for Different Food Applications," in *Advances in Food Extrusion Technology*, 2012. doi: 10.1201/b11286-8.

[52] A. Cohen, A. Laviv, P. Berman, R. Nashef, and J. Abu-Tair, "Mandibular reconstruction using stereolithographic 3-dimensional

printing modeling technology," *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology and Endodontology*, 2009, doi: 10.1016/j.tripleo.2009.05.023.

[53] M. Srinivas and B. S. Babu, "A Critical Review on Recent Research Methodologies in Additive Manufacturing," 2017. doi: 10.1016/j.matpr.2017.07.258.

[54] M. H. Ali, G. Issayev, E. Shehab, and S. Sarfraz, "A critical review of 3D printing and digital manufacturing in construction engineering," *Rapid Prototyping Journal*. 2022. doi: 10.1108/RPJ-07-2021-0160.

[55] S. L. Sing, J. An, W. Y. Yeong, and F. E. Wiria, "Laser and electron-beam powder-bed additive manufacturing of metallic implants: A review on processes, materials and designs," *Journal of Orthopaedic Research*. 2016. doi: 10.1002/jor.23075.

[56] S. Sun, M. Brandt, and M. Easton, "Powder bed fusion processes: An overview," in *Laser Additive Manufacturing: Materials, Design, Technologies, and Applications*, 2017. doi: 10.1016/B978-0-08-100433-3.00002-6.

[57] M. Ziaee and N. B. Crane, "Binder jetting: A review of process, materials, and methods," *Additive Manufacturing*. 2019. doi: 10.1016/j.addma.2019.05.031.

[58] M. Salmi, "Additive manufacturing processes in medical applications," *Materials*. 2021. doi: 10.3390/ma14010191.

[59] Y. Wang, Z. Xu, D. Wu, and J. Bai, "Current status and prospects of polymer powder 3D printing technologies," *Materials*, 2020, doi: 10.3390/ma13102406.

[60] J. S. Matsumoto *et al.*, "Three-dimensional physical modeling: Applications and experience at mayo clinic," *Radiographics*, 2015, doi: 10.1148/rg.2015140260.

[61] A. Alammar, J. C. Kois, M. Revilla-León, and W. Att, "Additive Manufacturing Technologies: Current Status and Future Perspectives," *Journal of Prosthodontics*. 2022. doi: 10.1111/jopr.13477.

[62] O. Gülcan, K. Günaydın, and A. Tamer, "The state of the art of material jetting—a critical review," *Polymers*. 2021. doi: 10.3390/polym13162829.

[63] A. Elkaseer, K. J. Chen, J. C. Janhsen, O. Refle, V. Hagenmeyer, and S. G. Scholz, "Material jetting for advanced applications: A state-of-the-art review, gaps and future directions," *Additive Manufacturing*. 2022. doi: 10.1016/j.addma.2022.103270.

[64] M. K. Patralekh and H. Lal, "3D Printing: Clinical Applications in Orthopaedics and Traumatology," in *The Hip Joint*, 2021. doi: 10.1201/9781003165460-6.

[65] A. V. Yarikov *et al.*, "Application of additive 3D printing technologies in neurosurgery, vertebrology and traumatology and orthopedics," *Journal of Clinical Practice*, 2021, doi: 10.17816/clinpract64944.

[66] I. Gibson, D. Rosen, B. Stucker, and M. Khorasani, "Sheet Lamination," in *Additive Manufacturing Technologies*, 2021. doi: 10.1007/978-3-030-56127-7_9.

[67] A. Dass and A. Moridi, "State of the art in directed energy deposition: From additive manufacturing to materials design," *Coatings*. 2019. doi: 10.3390/COATINGS9070418.

[68] D. G. Ahn, "Directed Energy Deposition (DED) Process: State of the Art," *International Journal of Precision Engineering and Manufacturing - Green Technology*. 2021. doi: 10.1007/s40684-020-00302-7.

[69] A. Tan, "3D printed medicines and medical devices – A US regulatory perspective,"

Regulatory Rapporteur, 2016.

[70] S. El-Sayegh, L. Romdhane, and S. Manjikian, “A critical review of 3D printing in construction: benefits, challenges, and risks,” *Archives of Civil and Mechanical Engineering*. 2020. doi: 10.1007/s43452-020-00038-w.

[71] B. Dorweiler, P. E. Baqué, R. Chaban, A. Ghazy, and O. Salem, “Quality control in 3D printing: Accuracy analysis of 3D-printed models of patient-specific anatomy,” *Materials*, 2021, doi: 10.3390/ma14041021.

[72] A. Ronca *et al.*, “A Comparative Study for Material Selection in 3D Printing of Scoliosis Back Brace,” *Materials*, 2022, doi: 10.3390/ma15165724.

[73] Z. Chen *et al.*, “3D printing of ceramics: A review,” *Journal of the European Ceramic Society*. 2019. doi: 10.1016/j.jeurceramsoc.2018.11.013.

[74] C. D. Christou and G. Tsoulfas, “Role of three-dimensional printing and artificial intelligence in the management of hepatocellular carcinoma: Challenges and opportunities,” *World Journal of Gastrointestinal Oncology*, 2022, doi: 10.4251/wjgo.v14.i4.765.

[75] K. Priyadarsini, A. K. Sivaraman, A. Q. Md, and A. Malibari, “Securing 3D Point and Mesh Fog Data Using Novel Chaotic Cat Map,” *Computers, Materials and Continua*, 2023, doi: 10.32604/cmc.2023.030648.

[76] R. Rana and S. Chhabra, “Challenges for Developing Navies to Adopt Industry 4.0,” 2019. doi: 10.24868/icmet.oman.2019.006.

[77] A. Zoabi *et al.*, “3D Printing and Virtual Surgical Planning in Oral and Maxillofacial Surgery,” *Journal of Clinical Medicine*, 2022, doi: 10.3390/jcm11092385.

[78] C. N. Thomas, S. Mavrommatis, L. K. Schroder, and P. A. Cole, “An overview of 3D printing and the orthopaedic application of patient-specific models in malunion surgery,” *Injury*, 2022, doi: 10.1016/j.injury.2021.11.019.

[79] Y. Fan, R. H. L. Wong, and A. P.-W. Lee, “Three-dimensional printing in structural heart disease and intervention,” *Annals of Translational Medicine*, 2019, doi: 10.21037/atm.2019.09.73.

[80] M. Küffer, D. Drescher, and K. Becker, “Application of the Digital Workflow in Orofacial Orthopedics and Orthodontics: Printed Appliances with Skeletal Anchorage,” *Applied Sciences (Switzerland)*, 2022, doi: 10.3390/app12083820.

[81] L. Suárez and M. del Mar Espinosa, “Assessment on the use of additive manufacturing technologies for acoustic applications,” *International Journal of Advanced Manufacturing Technology*, 2020, doi: 10.1007/s00170-020-05853-2.

[82] G. H. Snyder, M. J. Cotteleer, and B. Kotek, “3D opportunity in medical technology,” *Deloitte University Press*, 2014.

[83] D. Shilo, O. Emodi, O. Blanc, D. Noy, and A. Rachmiel, “Printing the Future—Updates in 3D Printing for Surgical Applications,” *Rambam Maimonides Medical Journal*, 2018, doi: 10.5041/rmmj.10343.

[84] A. Pugalendhi and R. Ranganathan, “A review of additive manufacturing applications in ophthalmology,” *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine*. 2021. doi: 10.1177/09544119211028069.