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Additive Manufacturing and Precision Engineering in Medical Devices

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ABSTRACT

This review shows how the integration of additive manufacturing with precision engineering is changing the face of medical device development. We have covered the main AM processes – FDM, SLA, SLS, SLM and EBM – and their role in everything from prosthetics to dental and surgical equipment. The paper examines the metals, polymers and composites that are essential for performance and biocompatibility. While there are challenges to be had with regulation and scaling, the advantages in efficiency and design are hard to ignore. With new trends in AI and bio printing on the horizon, the outlook for intelligent, patient-specific innovations is very promising.

INTRODUCTION

There is no denying that additive manufacturing, or AM as it is more often called (3D printing), has become a transformative force in the medical device and healthcare sectors. The process is the antithesis of conventional subtractive methods; rather than chipping away at a solid block with a machine or cutting tool to get what you need, AM takes a digital model and constructs an object from the ground up, one layer at a time [1]. It is an innovative way of working that allows for the creation of complex geometries and lightweight structures that would be out of reach for traditional manufacturers.

This is where precision engineering comes in. By definition, this discipline is about designing and making products with exacting accuracy and tight tolerances. In medicine, you cannot afford even the smallest dimensional error if you want to ensure a device is safe, compatible and effective [2]. Whether it is a surgical instrument, a prosthetic, an implant or a microfluidic diagnostic system, the clinical standards demand nothing less. Merging AM with precision engineering has done much to enhance the performance and functionality of modern devices in recent years [3].

Customization is perhaps the single biggest advantage AM offers in a medical setting. Standardized parts do not always yield the best results when every patient's anatomy is unique. With AM, engineers can use data from CT or MRI scans to produce patient-specific implants and prosthetics [4]. Not only does this personalized approach lead to better treatment outcomes and fewer complications, but it also means faster recovery and greater comfort for the patient. On top of that, the technology is well suited to rapid prototyping, giving healthcare professionals the ability to design, test and make changes to a device in short order before it goes into final production [5].

To make sure these devices have the right mechanical properties and a smooth finish, precision engineering is applied throughout the process. Advanced CAD and CAM systems, along with metrology, are put to work to control the parameters with the kind of repeatability and reliability that high-performance medical equipment requires [6]. Regulatory approval, quality assurance, material constraints and the cost of some applications are challenges that manufacturers and researchers are still grappling with. But with new developments on the horizon in areas like bio printing and AI-driven manufacturing, the outlook is strong [7]. Additive manufacturing and precision engineering are changing the face of the medical device industry, and their continued evolution will likely define the future of biomedical engineering.

Put simply, the marriage of additive manufacturing and precision engineering is changing the rules for how medical devices are put to paper and into production. When you apply high-accuracy engineering to digital fabrication methods, you can develop the kind of intricate, patient-specific answers that clinical standards demand. Such an approach does more than just improve safety and performance; it is a driver of innovation in personalized care. And with ongoing research pushing the boundaries of materials and digital tech, we can only expect the part played by additive manufacturing in medicine to expand. It is set to become a fixture in modern healthcare and the bedrock of biomedical engineering to come.

OVERVIEW OF ADDITIVE MANUFACTURING (AM) TECHNOLOGIES

At their core, AM technologies are a set of advanced fabrication tools for turning digital models into three-dimensional objects by depositing material in layers. They have made their mark in many industries, but in healthcare and medical device engineering the impact has been particularly profound. Where old-fashioned machining might leave you with a lot of waste, AM is efficient and opens the door to highly customized structures [8]. You will find them being used to make everything from tissue engineering scaffolds and anatomical models to dental restorations and surgical instruments. The workflow usually starts with a 3D model put together in CAD software or derived from an MRI or CT scan [9]. Slicing software then breaks that model down into thin cross-sections for the printer to follow. From there the machine will fuse or solidify the material in sequence until the piece is complete.

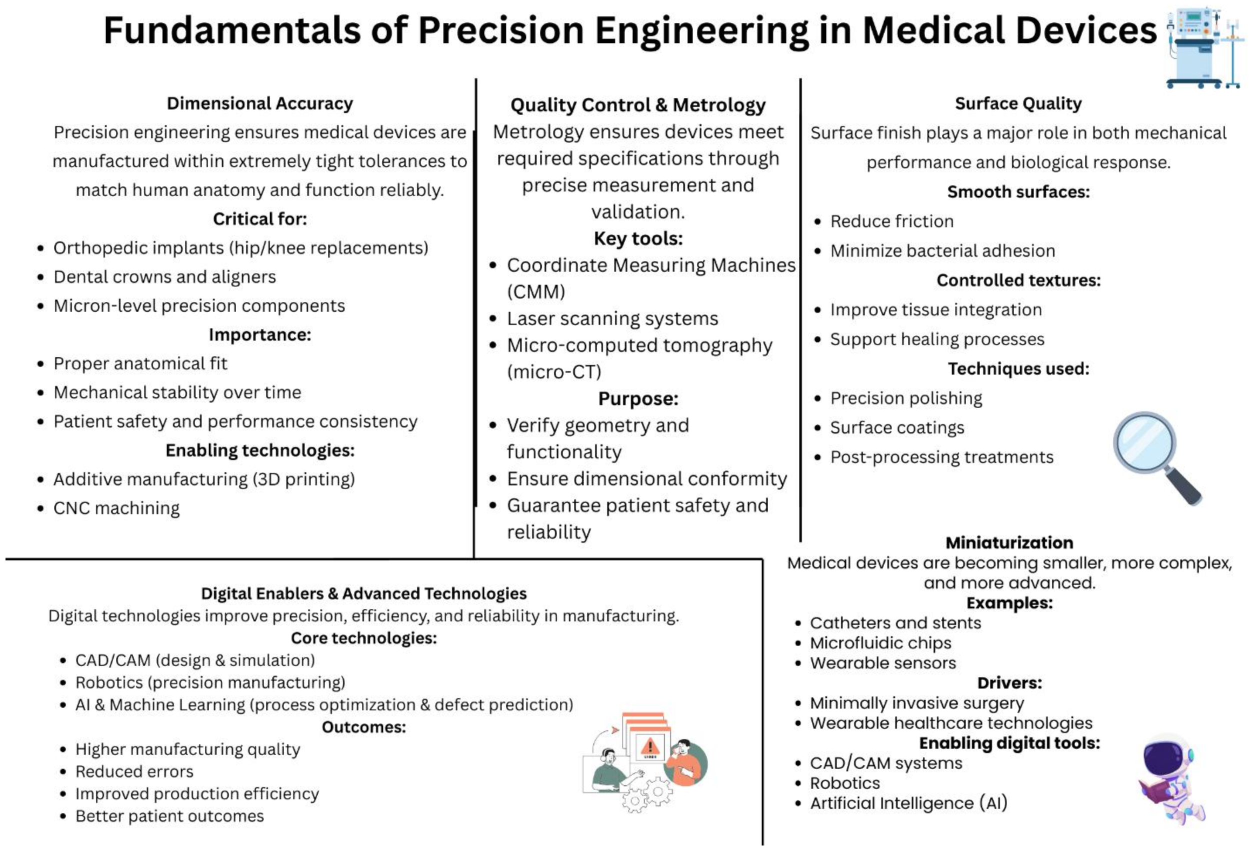
Take Fused Deposition Modeling (FDM) for instance. It is one of the most economical options, extruding thermoplastic through a hot nozzle to build up a part. It is fine for a surgical planning model or an educational tool, though you may not get the same level of surface finish or accuracy as with more sophisticated techniques [10]. For something like a hearing aid or a micro-scale component where you need top notch quality, you would look to vat photo polymerization such as Stereo lithography (SLA) or Digital Light Processing (DLP), which cures liquid resin with UV light [11].

Then there is Selective Laser Melting (SLM) and Sintering (SLS). These use a high-energy laser to bond metal or polymer powders into very strong, durable parts without the need for supports. SLM is indispensable for making titanium orthopedic implants because it can form the porous structures necessary for bone to integrate [12]. Electron Beam Melting (EBM) is similar but uses an electron beam in a vacuum to melt the powder; it is a favourite in aerospace and for biomedical implants given the superior mechanical properties and lower residual stresses. And for multi-material or color components needed in research or for anatomical models, you have Material and Binder Jetting [13].

FUNDAMENTALS OF PRECISION ENGINEERING IN MEDICAL DEVICES

Precision engineering is a branch of the discipline concerned with the design, development and manufacture of products that demand nothing short of the highest levels of accuracy, consistency and reliability. For the medical device industry, it is an indispensable part of the equation. The products in this field are put to work in sensitive environments where a minute dimensional error can compromise performance or patient safety and alter the outcome of a treatment [14]. With the appetite for more sophisticated healthcare technologies on the rise, precision engineering has become central to making today’s modern devices – from implants and prosthetics to surgical tools, diagnostic systems and minimally invasive instruments [15].

At its core is the principle of dimensional accuracy. A medical device has to be made within very tight tolerances to function as intended and be compatible with human anatomy. Take orthopedic implants like hip or knee replacements: they need exact dimensions to sit right in the patient's body and offer mechanical stability over time [16]. The same goes for dental crowns and aligners, which are produced to the micron for comfort and efficacy. To get there, manufacturers will often turn to advanced methods like additive manufacturing or computer numerical control (CNC) machining [17].



Fundamentals of Precision Engineering in Medical Devices

Dimensional Accuracy
Precision engineering ensures medical devices are manufactured within extremely tight tolerances to match human anatomy and function reliably.
Critical for:
- Orthopedic implants (hip/knee replacements)
- Dental crowns and aligners
- Micron-level precision components

Importance:
- Proper anatomical fit
- Mechanical stability over time
- Patient safety and performance consistency

Enabling technologies:
- Additive manufacturing (3D printing)
- CNC machining

Quality Control & Metrology
Metrology ensures devices meet required specifications through precise measurement and validation.
Key tools:
- Coordinate Measuring Machines (CMM)
- Laser scanning systems
- Micro-computed tomography (micro-CT)

Purpose:
- Verify geometry and functionality
- Ensure dimensional conformity
- Guarantee patient safety and reliability

Surface Quality
Surface finish plays a major role in both mechanical performance and biological response.
Smooth surfaces:
- Reduce friction
- Minimize bacterial adhesion

Controlled textures:
- Improve tissue integration
- Support healing processes

Techniques used:
- Precision polishing
- Surface coatings
- Post-processing treatments

Digital Enablers & Advanced Technologies
Digital technologies improve precision, efficiency, and reliability in manufacturing.
Core technologies:
- CAD/CAM (design & simulation)
- Robotics (precision manufacturing)
- AI & Machine Learning (process optimization & defect prediction)

Outcomes:
- Higher manufacturing quality
- Reduced errors
- Improved production efficiency
- Better patient outcomes

Miniaturization
Medical devices are becoming smaller, more complex, and more advanced.
Examples:
- Catheters and stents
- Microfluidic chips
- Wearable sensors

Drivers:
- Minimally invasive surgery
- Wearable healthcare technologies

Enabling digital tools:
- CAD/CAM systems
- Robotics
- Artificial Intelligence (AI)

Figure 1. Fundamentals of Precision Engineering in Medical Devices

Then there is the matter of surface quality. The finish on an implant or instrument has a direct bearing on how it performs both mechanically and biologically. You want smooth surfaces to keep down friction and bacterial build-up, but at times a controlled texture is better for tissue integration and healing. That is why you will see a lot of precision polishing, post-processing and coating technologies being put to use [18]. Quality control and metrology are also key. Metrology, the science of measurement, is what allows us to verify a device's geometry and functionality. We rely on things like coordinate measuring machines, laser scanners and micro-computed tomography to make sure parts are up to spec. In healthcare you cannot have any let-ups in this regard; a device failure is not something one can afford given the potential for serious complications [19].

Miniaturization is another hallmark of the field. As we see with wearable tech and in minimally invasive surgery, devices are getting smaller and more complicated. Making a catheter, stent or microfluidic chip requires a level of precision in the design and build process that is only possible with the help of digital tools like CAD/CAM, robotics and AI. These technologies do more than just optimize the process; they cut down on errors and boost efficiency [20].

MATERIALS IN ADDITIVE MANUFACTURING FOR MEDICAL USE

When it comes to additive manufacturing (AM), the materials you choose are paramount since they dictate the durability, biocompatibility and overall performance of the device. What you use will depend on the clinical needs and the technology at hand. The healthcare sector makes use of everything from metals and polymers to composites and bio-based materials to put out custom, high-calibre products like tissue engineering scaffolds or surgical instruments [21]. Metals and their alloys are by far the most popular in medical AM for their mechanical soundness.

Titanium and Ti-6Al-4V in particular are the go-to for orthopedic and dental work because of how well they hold up and their compatibility with bone. You will also find stainless steel and cobalt-chromium in joint replacements and other instruments for their wear resistance [22]. Technologies like Selective Laser Melting (SLM) and Electron Beam Melting (EBM) are routinely used to form these into complex, patient-specific shapes. Polymers are equally important. Fused Deposition Modeling and similar techniques make extensive use of thermoplastics like PEEK, nylon, ABS and polylactic acid (PLA). PLA is a favourite for temporary models and tissue engineering as it is biodegradable, while PEEK is prized in the biomedical world for its strength and ability to be sterilized [23].

For stereolithography and DLP printing, photopolymer resins are the material of choice when you need the fine detail and smooth finish required for hearing aids or surgical guides. For hardness and bioactivity, one might look to ceramics. Hydroxyapatite and biogas are often used in implant coatings and bone tissue engineering as they are akin to the mineral makeup of human bone and can encourage growth [24]. Their brittleness is a drawback for load-bearing uses, however. Composite materials, such as polymer-ceramics, are a way to get the best of both worlds, and researchers are hard at work on smart and biodegradable composites for the future [25].

INTEGRATION OF ADDITIVE MANUFACTURING WITH PRECISION ENGINEERING

The integration of additive manufacturing (AM) with precision engineering represents a significant advancement in modern medical device development. This combination brings together the design flexibility and customization capabilities of AM with the accuracy, control, and quality assurance principles of precision engineering [26]. As a result, it enables the production of highly complex, patient-specific medical devices with exceptional dimensional accuracy, functional performance, and reliability. This integration is particularly important in healthcare, where even minor deviations in device geometry or surface quality can impact patient safety and treatment outcomes [27].

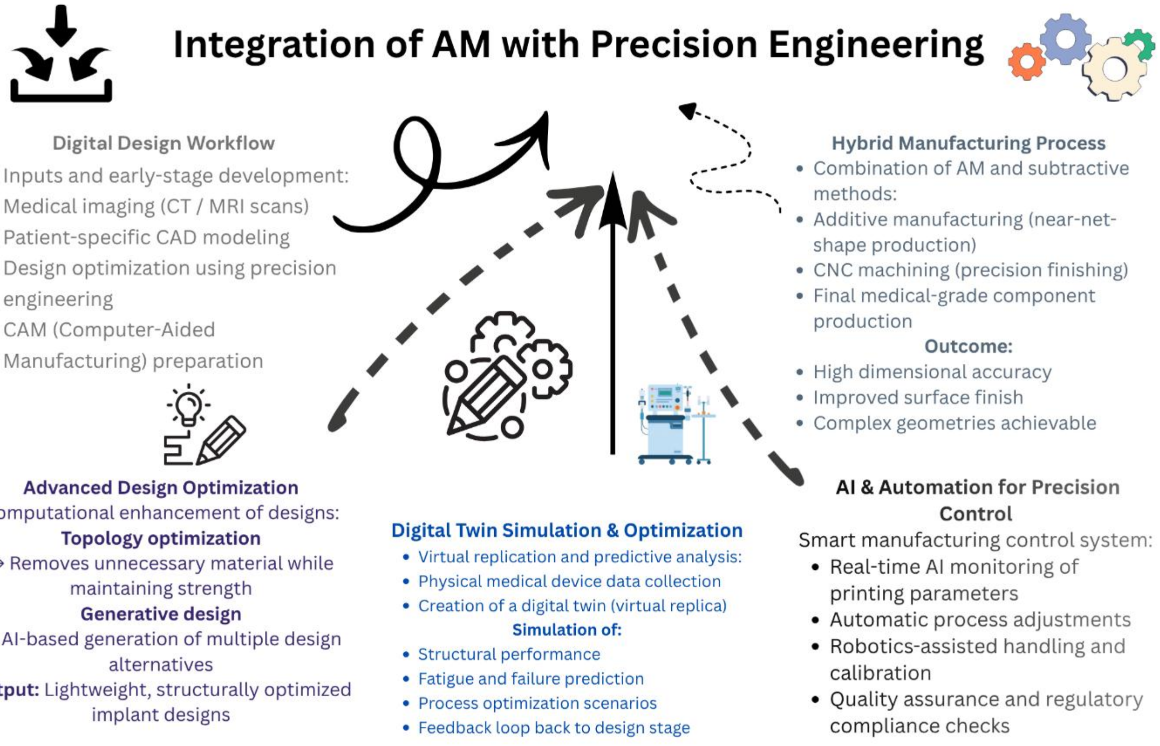


Figure 2. Integration of AM with Precision Engineering

One of the key components of this integration is the use of digital design workflows, including computer-aided design (CAD) and computer-aided manufacturing (CAM) systems. CAD software allows engineers to create detailed 3D models of medical devices based on patient anatomy, often derived from medical imaging techniques such as CT and MRI scans [28]. These digital models are then optimized using precision engineering principles to ensure structural integrity, functional efficiency, and compliance with clinical requirements. CAM systems translate these designs into machine instructions that guide additive manufacturing equipment with high accuracy [29].

Topology optimization and generative design are advanced computational techniques that further enhance this integration. Topology optimization removes unnecessary material from a design while maintaining required strength and performance, resulting in lightweight yet strong structures. Generative design goes a step further by using algorithms and artificial intelligence to explore multiple design solutions based on defined constraints [30]. These methods are particularly useful in medical implants, where reducing weight while maintaining mechanical stability can improve patient comfort and recovery.

Hybrid manufacturing approaches also play a significant role in combining additive manufacturing with precision engineering. In many cases, AM is used to produce complex near-net-shape components, which are then refined using subtractive processes such as CNC machining to achieve ultra-high dimensional accuracy and surface finish. This combination ensures both design flexibility and precision performance, making it ideal for critical medical applications such as orthopedic implants and surgical tools [31].

The integration of artificial intelligence (AI) and automation technologies further enhances precision in additive manufacturing. AI-based monitoring systems can analyze printing parameters in real time, detect defects, and adjust process conditions to maintain consistent quality. Robotics and automated calibration systems improve repeatability and reduce human error, ensuring that medical devices meet strict regulatory standards [32]. Another important aspect is the development of digital twins, which are virtual replicas of physical devices or processes. Digital twins allow engineers to simulate performance, predict failures, and optimize manufacturing processes before actual production. This reduces development time and improves product reliability [33].

APPLICATIONS IN MEDICAL DEVICES

When you put additive manufacturing (AM) together with precision engineering, the possibilities for medical device applications are greatly broadened. This kind of technological synergy has been a game changer in traditional healthcare manufacturing, making it possible to produce patient-specific solutions that are as complex as they are highly customized [34]. The result is better treatment outcomes and greater comfort for the patient, not to mention lower surgical risks. You will find AM in use today in a host of medical disciplines – orthopedics, dentistry, surgery, prosthetics, cardiovascular medicine and regenerative medicine to name a few [35].

Take orthopedic implants for instance. It is perhaps the most well-known application. With AM you can make hip, knee, spinal or cranial implants that are a perfect anatomical match for the patient. Materials like titanium and cobalt-chromium alloys are the go-to for their biocompatibility and strength. But the real advantage is being able to engineer porous structures for osseointegration; this lets bone tissue take hold on the implant surface for better stability over time [36]. And precision engineering is there to see that these parts conform to the exacting tolerances needed for safe implantation. Dentistry has been revolutionized by the technology as well. Intraoral scanners provide digital impressions that are turned into 3D models for the quick fabrication of crowns, bridges, clear aligners and dentures with an excellent fit [37]. Stereo lithography and DLP are popular choices for the smooth finish and resolution they give. It is a far cry from old-fashioned casting methods in terms of speed and has done much to please patients.

Then there are the fast-growing cardiovascular uses. Surgeons can now plan procedures with the help of patient-specific heart models, or have stents and vascular grafts made to order. These tools let them

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get a good look at complicated anatomy beforehand, which minimizes risk. We are even seeing work with biodegradable materials for temporary implants that will safely dissolve once they have done their job [38]. Surgical instruments and guides are another area where AM is prevalent. Custom guides are invaluable in complex or minimally invasive operations to ensure everything is properly aligned. You also see more lightweight, ergonomic instruments being made that are easier on the surgeon's hands [39].

For prosthetics and wearables like exoskeleton components or braces, the technology allows for a level of personalization in both looks and function that was not before possible. In the newer realm of bio printing and tissue engineering, AM is what makes it possible to put down scaffolds of biocompatible material to encourage cell growth. Some researchers are already looking at 3D printing skin, cartilage and organ-like structures for eventual transplantation [40]. All in all, the way AM is fusing innovation with precision is reshaping modern healthcare.

ADVANTAGES OF ADDITIVE MANUFACTURING IN MEDICAL DEVICE PRODUCTION

There is no question that AM has had an impact on biomedical engineering. Paired with precision engineering, it brings a host of benefits in terms of efficiency, sustainability and patient care. Customization is at the top of the list. Where you might be limited to standard sizes with conventional methods, AM lets you work from CT or MRI data to build a prosthetic or surgical tool that is tailored to the individual. That means a better fit and less chance of complications for the patient. It also cuts down on time and expense for complex parts [41].

There is no need for costly molds or the various steps of traditional production; once the digital file is ready, you can make the device. That is a distinct advantage in an emergency. And designers can do some rapid prototyping to iron out any kinks before the final run. The performance of the devices is enhanced too. You can create intricate internal channels and lattice work that would be hard to do otherwise [42]. A porous surface on an implant, for example, is good for bone ingrowth. You can keep things lightweight without sacrificing strength.

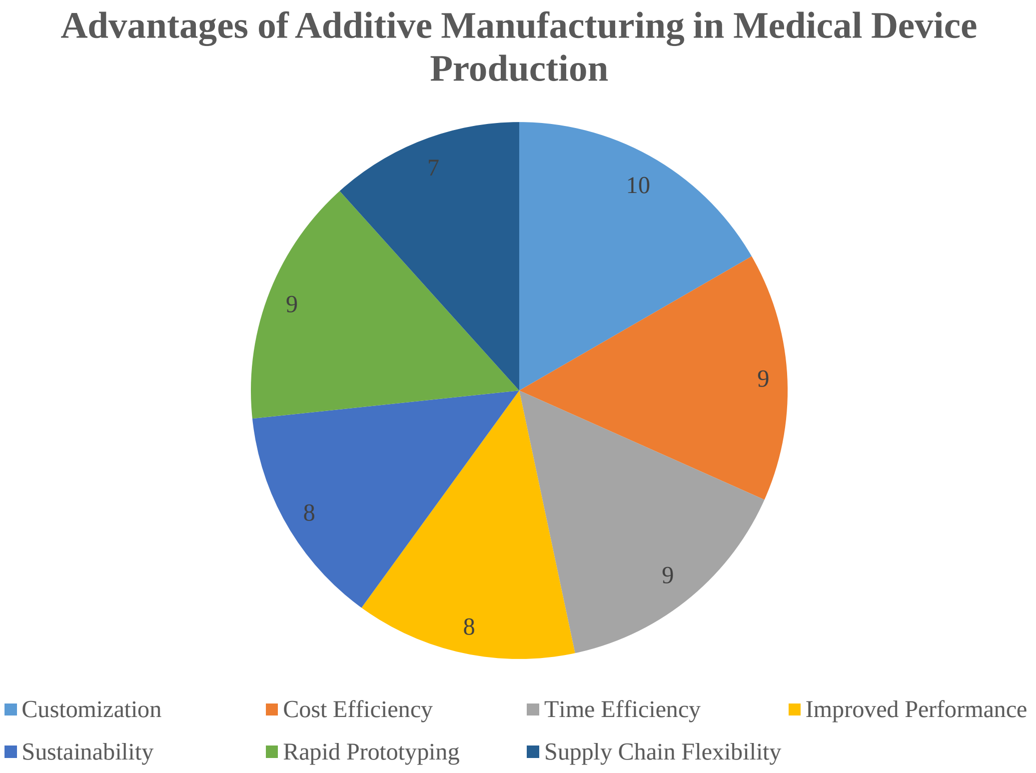

Figure 3. Advantages of Additive Manufacturing in Medical Device Production

From a sustainability standpoint, AM is more efficient. Because you are building up layer by layer rather than machining away at a block, you generate very little waste. It also means you can innovate faster, designing and testing new ideas for smart implants or regenerative medicine in short order. There is the matter of the supply chain. Being able to manufacture on demand or locally takes some of the pressure off centralized facilities and their logistics [43].

There is no better place to see the value of additive manufacturing than in remote or resource-poor healthcare environments. In the production of medical devices, it brings a host of advantages: from greater design freedom and efficiency to sustainability and the ability to innovate and personalize. It is these very benefits that are propelling a worldwide move toward more sophisticated, patient-focused care [44].

CHALLENGES AND LIMITATIONS

For all its rapid growth and clear merits in making medical devices, additive manufacturing (AM) has yet to be fully embraced in clinical and industrial circles. There are obstacles to overcome on regulatory, technical, material and economic fronts if we are to use it safely and effectively in healthcare. Regulatory and safety compliance is perhaps the most pressing issue [45]. The FDA, EMA and other national bodies have exacting standards that every device must satisfy. AM's inherent

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flexibility and the complex geometries it allows make for a hard-to-standardize process; you cannot be sure of consistent quality from one batch to the next [46].

Then there is the matter of patient-specific devices which may need to be validated individually, putting the brakes on commercialization. We are still working toward universally accepted standards for AM-made devices. Mechanical reliability is another area of concern. You can print a complicated structure with AM, but the resulting part will not always have the same mechanical properties as something made the old-fashioned way [47]. Anisotropy is a case in point: the material's behaviour can change with the direction of the print, compromising fatigue resistance and strength.

In an implant under constant load, that is a long-term worry. You have to be meticulous with your process optimization and post-processing to guarantee structural integrity. Speaking of post-processing, surface defects can be a problem [48]. To get the surface quality you need, many parts will have to be polished, coated or heat treated. A rough finish invites bacterial adhesion and wear, and in precision work even a small imperfection can ruin a device's performance. It is an essential step, but a costly and time-consuming one [49].

And while AM is the way to go for custom, low-volume work, it does not scale well for mass production. Printing speed and cost put limits on what you can do when you are churning out large quantities, so for now it is confined to things like prosthetics and surgical guides rather than disposable items. Material availability is also a hindrance; not every medically approved substance works with AM, some degrade in the process, and we simply do not have enough long-term clinical data on many of the newer options [50].

RECENT ADVANCES AND EMERGING TRENDS

But the field is moving fast. With new thinking in materials science and biomedical engineering, AM is becoming something more than just a prototyping tool; it is enabling solutions that are biologically integrated and far more intelligent. We are seeing 4D printing make inroads in healthcare. This is a step beyond 3D printing in that the structures created can alter their shape or function over time when exposed to pH, moisture or temperature [51]. It is being looked at for smart implants and self-adjusting stents that will conform to the body once they are in place, opening up new avenues for minimally invasive procedures.

Smart and bioactive materials are also on the rise. These are not passive supports; they interact with the biology around them. A bioactive coating might encourage bone growth to forestall rejection, while smart polymers can be used for localized drug delivery right at the site of the implant, which cuts down on side effects. Nanotechnology is finding its way into the mix as well. By adding nanoparticles to the printing material, you can boost the antimicrobial and mechanical qualities of the device. Nanostructured surfaces are proving their worth in regenerative medicine by helping cells adhere and tissue to regenerate [52]. Then there is the influence of Industry 4.0 and digital twin technology. Engineers can now run a virtual replica of a device through real-time simulations to spot any potential failures before they ever start physical production [53].

Couple that with AI and machine learning to handle defect detection and design optimization, and you have a workflow that is both precise and reliable. The combination of 4D printing, nanotech and digital intelligence is redefining what is possible. These recent strides in additive manufacturing are setting the stage for a new generation of medical devices that are more efficient and personalized than we have seen before [54].

FUTURE PERSPECTIVES AND RESEARCH DIRECTIONS

There is little doubt that the future of additive manufacturing (AM) in the medical device sector is a bright one. Current research is making great strides in precision, material scope and the use of digital tech, and as healthcare gravitates toward more personal and minimally invasive care, AM and precision engineering are set to be at the heart of biomedical innovation for the next generation. Take the push for patient-specific solutions, for instance [55]. This is perhaps the most significant direction for the field. Thanks to better imaging, computational models and AI, we can now design implants and surgical tools that fit an individual's anatomy with exactitude. Down the line, you may see real-time data from imaging systems feeding straight into automated AM units, producing custom devices with little need for human input [56].

Then there is the matter of bio fabrication and bio printing. Scientists are busy trying to make functional organs and tissues out of living cells and biomaterials. For now, you will find applications in skin or vascular grafts, but the goal is to eventually print an organ for transplant. That would do wonders for regenerative medicine and ease the strain on donor lists [57]. On the materials front, researchers are after new biomaterials with greater strength and biological activity. They are looking at smart materials that react to their environment, ones that can self-heal, or biodegradable types that will safely break down in the body. All of this serves to make implants safer and more efficient [58]. You can also expect AI and robotics to have a profound effect on AM systems. Robotic automation brings a level of repeatability and precision that is hard to match, while AI can optimize designs and speed up development. Predictive analytics will help keep defects to a minimum. And let us not forget sustainability; the aim is to have AM systems that are kinder to the environment, using less energy and recyclable, bio-based materials [59].

All of this has to work within a regulatory framework. We can expect global standards to evolve to ensure safety and quality. Researchers are in close contact with the regulators to put in place the right validation and certification for these technologies. In short, the way forward for AM in medical devices is through a deeper melding with digital and biological systems to create healthcare that is more intelligent and patient-focused [60].

CONCLUSION

When you look at the principles, the technology and the challenges involved, it is clear that AM coupled with precision engineering has become a transformative element in how medical devices are made. It is an approach that is reshaping modern healthcare by offering a degree of accuracy and customization that conventional methods simply cannot. After all, AM builds from a digital model, layer upon layer, giving designers a freedom they did not have before, while precision engineering makes sure those complex structures are reliable and safe. The array of technologies available is telling: Fused Deposition Modeling, Stereo lithography, Selective Laser Sintering and Melting, and Electron Beam Melting each have their place depending on what is required in terms of resolution or mechanical performance. Add to that the right materials – titanium and cobalt-chromium for a strong implant, PEEK or PLA for flexibility, or ceramics for bone regeneration – and you have a recipe for high-quality clinical devices.

We see the impact in orthopedics, dentistry, cardiovascular work and beyond. The benefits are obvious in the form of less waste, quicker prototyping and better outcomes for the patient. There are still hurdles to clear, be it surface quality, scalability or getting regulatory approval, and ensuring long-term consistency is no small task. But research is moving fast to overcome these. In the years to come, we will likely see 4D printing, nanotechnology and digital twins change the game once more, creating devices that are more adaptive and biologically integrated. The marriage of additive manufacturing and precision engineering is a paradigm shift. It connects the digital with the clinical in a way that will define the future of medicine and patient care.

REFERENCES

[1]. Li C, Pisignano D, Zhao Y, Xue J. Advances in medical applications of additive manufacturing. Engineering. 2020 Nov 1;6(11):1222-31.

[2]. Francis MP, Kemper N, Maghdouri-White Y, Thayer N. Additive manufacturing for biofabricated medical device applications. InAdditive manufacturing 2018 Jan 1 (pp. 311-344). Butterworth-Heinemann.

[3]. Ionescu N, Ulmeanu ME, Doicin CV, Ionescu C, Spânu P. Prescribed precision for medical products obtained with additive manufacturing technologies. InIOP Conference Series: Materials Science and Engineering 2022 Nov 1 (Vol. 1268, No. 1, p. 012004). IOP Publishing.

[4]. Ionescu N, Ulmeanu ME, Doicin CV, Ionescu C, Spânu P. Prescribed precision for medical products obtained with additive manufacturing technologies. InIOP Conference Series: Materials Science and Engineering 2022 Nov 1 (Vol. 1268, No. 1, p. 012004). IOP Publishing.

[5]. Javaid M, Haleem A, Siddiqui TU. Advancing Personalized Medicine: The Role of Additive Manufacturing in Patient-Specific Implants and Tissue Engineering. InBiomaterials in Orthopaedics & Trauma: Current Status and Future Trends in Revolutionizing Patient Care 2025 Apr 23 (pp. 239-252). Singapore: Springer Nature Singapore.

[6]. Qiu G, Ding W, Tian W, Qin L, Zhao Y, Zhang L, Lu J, Chen D, Yuan G, Wu C, Lu B. Medical additive manufacturing: from a frontier technology to the research and development of products. Engineering. 2020 Nov 1;6(11):1217-21.

[7]. Sheoran AJ, Kumar H, Arora PK, Moona G. Bio-medical applications of additive manufacturing: a review. Procedia Manufacturing. 2020 Jan 1;51:663-70.

[8]. Bastin A, Huang X. Progress of additive manufacturing technology and its medical applications. ASME Open Journal of Engineering. 2022 Jan 1;1.

[9]. Sun B, Ma Q, Wang X, Liu J, Rejab MR. Additive manufacturing in medical applications: a brief review. InIOP conference series: materials science and engineering 2021 Feb 1 (Vol. 1078, No. 1, p. 012007). IOP Publishing.

[10]. Chin SY, Poh YC, Kohler AC, Compton JT, Hsu LL, Lau KM, Kim S, Lee BW, Lee FY, Sia SK. Additive manufacturing of hydrogel-based materials for next-generation implantable medical devices. Science robotics. 2017 Jan 4;2(2):eaah6451.

[11]. Salmi M, Paloheimo KS, Tuomi J, Wolff J, Mäkitie A. Accuracy of medical models made by additive manufacturing (rapid manufacturing). Journal of Cranio-Maxillofacial Surgery. 2013 Oct 1;41(7):603-9.

[12]. Pathak K, Saikia R, Das A, Das D, Islam MA, Pramanik P, Parasar A, Borthakur PP, Sarmah P, Saikia M, Borthakur B. 3D printing in biomedicine: advancing personalized care through additive manufacturing. Exploration of Medicine. 2023 Dec 29;4(6):1135-67.

[13]. Trivedi M, Jee J, Silva S, Blomgren C, Pontinha VM, Dixon DL, Van Tassel B, Bortner MJ, Williams C, Gilmer E, Haring AP. Additive manufacturing of pharmaceuticals for precision medicine applications: A review of the promises and perils in implementation. Additive Manufacturing. 2018 Oct 1;23:319-28.

[14]. Alex Y, Shanmugam R, Salunkhe S, Čep R. Advancement of additive manufacturing technology in the development of personalized in vivo and in vitro prosthetic implants. Reviews on Advanced Materials Science. 2025 May 26;64(1):20250109.

[15]. Javaid M, Haleem A. Additive manufacturing applications in medical cases: A literature based review. Alexandria Journal of Medicine. 2018 Dec 1;54(4):411-22.

[16]. Gibson I, Srinath A. Simplifying medical additive manufacturing: making the surgeon the designer. Procedia Technology. 2015 Jan 1;20:237-42.

[17]. Kennedy SM, K A, V E, Rb JR. Transformative applications of additive manufacturing in biomedical engineering: bioprinting to surgical innovations. Journal of Medical Engineering & Technology. 2024 May 18;48(4):151-68.

[18]. Kumar V, Prakash C, Babbar A, Choudhary S, Sharma A, Uppal AS. Additive manufacturing in biomedical engineering: present and future applications. InAdditive Manufacturing Processes in Biomedical Engineering 2022 Jul 29 (pp. 143-164). CRC Press.

[19]. Ali MA, Rajabi M, Sali SS. Additive manufacturing potential for medical devices and technology. Current opinion in chemical engineering. 2020 Jun 1;28:127-33.

[20]. Vanderbilt MP, Lissy DA, McLaughlin B. Additive Manufacturing for Orthopedic Implants: Material and Process Selection, Validation Activities, and Regulatory Submissions. John Wiley & Sons; 2026 Apr 20.

[21]. Tan D, Nokhodchi A, Maniruzzaman M. 3D and 4D printing technologies: innovative process engineering and smart additive manufacturing. 3D and 4D printing in biomedical applications: process engineering and additive manufacturing. 2019 Feb 19:25-52.

[22]. Martinez-Marquez D, Jokymaityte M, Mirnajafizadeh A, Carty CP, Lloyd D, Stewart RA. Development of 18 quality control gates for additive manufacturing of error free patient-specific implants. Materials. 2019 Sep 24;12(19):3110.

[23]. Jelínek F, Breedveld P. Design for additive manufacture of fine medical instrumentation—DragonFlex case study. Journal of Mechanical Design. 2015 Nov 1;137(11):111416.

[24]. Zhai Y, Zhang H, Wang J, Zhao D. Research progress of metal-based additive manufacturing in medical implants. Reviews on Advanced Materials Science. 2023 Nov 29;62(1):20230148.

[25]. Adamo JE, Grayson WL, Hatcher H, Brown JS, Thomas A, Hollister S, Steele SJ. Regulatory interfaces surrounding the growing field of additive manufacturing of medical devices and biologic products. Journal of clinical and translational science. 2018 Oct;2(5):301-4.

[26]. Geng Z, Bidanda B. Medical applications of additive manufacturing. InBio-materials and prototyping applications in medicine 2020 Oct 17 (pp. 97-110). Cham: Springer International Publishing.

[27]. Ariz A, Tasneem I, Bharti D, Vaish A, Haleem A, Javaid M. Is additive manufacturing of patient-specific implant beneficial for orthopedics. Apollo Medicine. 2021 Mar;18(1):33-40.

[28]. Cornejo J, Cornejo-Aguilar JA, Vargas M, Helguero CG, Milanezi de Andrade R, Torres-Montoya S, Asensio-Salazar J, Rivero Calle A, Martínez Santos J, Damon A, Quiñones-Hinojosa A. Anatomical engineering and 3D printing for surgery and medical devices: international review and future exponential innovations. BioMed research international. 2022;2022(1):6797745.

[29]. Amaya-Rivas JL, Perero BS, Helguero CG, Hurel JL, Peralta JM, Flores FA, Alvarado JD. Future trends of additive manufacturing in medical applications: An overview. Heliyon. 2024 Mar 15;10(5).

[30]. Laskowska D, Mitura K, Ziółkowska E, Bałasz B. Additive manufacturing methods, materials and medical applications-the review. Journal of Mechanical and Energy Engineering. 2021 Aug 12;5(1):15-30.

[31]. Awasthi A, Saxena KK, Dwivedi RK. An investigation on classification and characterization of bio materials and additive manufacturing techniques for bioimplants. Materials Today: Proceedings. 2021 Jan 1;44:2061-8.

[32]. Ciurana J. Designing, prototyping and manufacturing medical devices: an overview. International Journal of Computer Integrated Manufacturing. 2014 Oct 3;27(10):901-18.

[33]. Hossain MS, Gonzalez JA, Hernandez RM, Shuvo MA, Mireles J, Choudhuri A, Lin Y, Wicker RB. Fabrication of smart parts using powder bed fusion additive manufacturing technology. Additive Manufacturing. 2016 Apr 1;10:58-66.

[34]. Singh S, Kumar M, Kumar D, Kumar S, Chopra S, Bhatia A. Therapeutic precision: unveiling the potential of 3D printing in drug delivery, tissue engineering, and regenerative medicine. 3D Printing and Additive Manufacturing. 2025 Oct 1;12(5):447-73.

[35]. Leong WY. Circular Economy Through Green Additive Manufacturing in Medical Device Manufacturing. Engineering Proceedings. 2026 Feb 20;129(1):1.

[36]. Barnhill J, Gaston JD, Deffenbaugh PI, Wagner L, Liacouras PC, Ho VB. Additive manufacturing for fabrication of point-of-care therapies in austere environments. Military medicine. 2023 Jul 1;188(7-8):e1847-53.

[37]. Tiwary VK, Arunkumar P, Malik VR. 7 Hybrid Additive-Subtractive Manufacturing: The Integration of 3D Printing and Precision Machining for Advanced Manufacturing. Hybrid Manufacturing Processes: From Micromachining to Additive Manufacturing. 2026 Jun 22:159.

[38]. Chirume WM, Guo C, Zheng D, Ma F, Fan C, Li L, Wang L, Zhou C, Kong Q. Advanced additive manufacturing in orthopedics: a comprehensive review of biomaterials, structural

design, biological functions and clinical technology applications. RSC advances. 2026;16(13):11668-85.

[39]. Gioumouxouzis CI, Karavasili C, Fatouros DG. Recent advances in pharmaceutical dosage forms and devices using additive manufacturing technologies. Drug discovery today. 2019 Feb 1;24(2):636-43.

[40]. Kantaros A, Petrescu FI, Abdoli H, Diegel O, Chan S, Iliescu M, Ganetsos T, Munteanu IS, Ungureanu LM. Additive manufacturing for surgical planning and education: a review. Applied Sciences. 2024 Mar 18;14(6):2550.

[41]. Szymczyk-Ziółkowska P, Łabowska MB, Detyna J, Michalak I, Gruber P. A review of fabrication polymer scaffolds for biomedical applications using additive manufacturing techniques. Biocybernetics and Biomedical Engineering. 2020 Apr 1;40(2):624-38.

[42]. Told R, Ujfalusi Z, Pentek A, Kerenyi M, Banfai K, Vizi A, Szabo P, Melegh S, Bovari-Biri J, Pongracz JE, Maroti P. A state-of-the-art guide to the sterilization of thermoplastic polymers and resin materials used in the additive manufacturing of medical devices. Materials & design. 2022 Nov 1;223:111119.

[43]. Hengsbach S, Lantada AD. Rapid prototyping of multi-scale biomedical microdevices by combining additive manufacturing technologies. Biomedical microdevices. 2014 Aug;16(4):617-27.

[44]. Behera D, Cullinan M. Current challenges and potential directions towards precision microscale additive manufacturing–Part I: Direct ink writing/jetting processes. Precision Engineering. 2021 Mar 1;68:326-37.

[45]. Tang Y, Zhang Y, Meng Z, Sun Q, Peng L, Zhang L, Lu W, Liang W, Chen G, Wei Y. Accuracy of additive manufacturing in stomatology. Frontiers in Bioengineering and Biotechnology. 2022 Aug 16;10:964651.

[46]. Tariq A, Arif ZU, Khalid MY, Hossain M, Rasool PI, Umer R, Ramakrishna S. Recent advances in the additive manufacturing of stimuli-responsive soft polymers. Advanced Engineering Materials. 2023 Nov;25(21):2301074.

[47]. Huang SH, Liu P, Mokasdar A, Hou L. Additive manufacturing and its societal impact: a literature review. The International journal of advanced manufacturing technology. 2013 Jul;67(5):1191-203.

[48]. Chowdhury MM, Scerri M, Shahriar S, Skellern K. Digital transformation of supply chain: a study on additive manufacturing practice in medical device in Australia. Journal of Enterprise Information Management. 2024 Jul 17;37(4):1117-39.

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[49]. Bhatia A, Sehgal AK. Additive manufacturing materials, methods and applications: A review. Materials Today: Proceedings. 2023 Jan 1;81:1060-7.

[50]. Jose RR, Rodriguez MJ, Dixon TA, Omenetto F, Kaplan DL. Evolution of bioinks and additive manufacturing technologies for 3D bioprinting. ACS biomaterials science & engineering. 2016 Oct 10;2(10):1662-78.

[51]. Lam J, Kwee BJ, Ricles LM, Sung KE. Development of additive manufacturing-based medical products for clinical translation and marketing. InBone Tissue Engineering: Bench to Bedside Using 3D Printing 2022 Mar 8 (pp. 267-292). Cham: Springer International Publishing.

[52]. Upadhyay P, Agarwal S, Chauhan R, Upadhyay S. Fundamental Concepts of Additive Manufacturing in the Biomedical Field. InHandbook of 3D Printing in Biomedical Applications 2025 May 30 (pp. 1-20). CRC Press.

[53]. Huang Y, Schmid SR. Additive manufacturing for health: state of the art, gaps and needs, and recommendations. Journal of Manufacturing Science and Engineering. 2018 Sep 1;140(9):094001. Garcia-Leiner M, Ghita O, McKay R, Kurtz SM. Additive manufacturing of polyaryletherketones. InPEEK Biomaterials Handbook 2019 Jan 1 (pp. 89-103). William Andrew Publishing.

[54]. Savsani S, Singh S, Mali HS. Additive manufacturing for prostheses development: state of the art. Rapid Prototyping Journal. 2023 Apr 4;29(4):741-65.

[55]. Bibb R, Thompson D, Winder J. Computed tomography characterisation of additive manufacturing materials. Medical engineering & physics. 2011 Jun 1;33(5):590-6.

[56]. Velu R, Jayashankar DK, Subburaj K. Additive processing of biopolymers for medical applications. InAdditive Manufacturing 2021 Jan 1 (pp. 635-659). Elsevier.

[57]. Pathapalli VR, AC UM, Kasu SR, Doni MK. A review on additive manufacturing: its applications and future directions. Rapid Prototyping Journal.:1-22.

[58]. Ikram H, Al Rashid A, Koç M. Additive manufacturing of smart polymeric composites: Literature review and future perspectives. Polymer Composites. 2022 Sep;43(9):6355-80.

[59]. Ikram H, Al Rashid A, Koç M. Additive manufacturing of smart polymeric composites: Literature review and future perspectives. Polymer Composites. 2022 Sep;43(9):6355-80.

[60]. Renjith SC, Park K, Okudan Kremer GE. A design framework for additive manufacturing: Integration of additive manufacturing capabilities in the early design process. International Journal of Precision Engineering and Manufacturing. 2020 Feb;21(2):329-45.