



Personalized 3D-printed bone plates in fracture management: recent advances and future perspectives

Wenchuan Li*

The First Clinical Medical College of Guangxi Medical University, Nanning 530021, Guangxi, China.

***Correspondence to:** Wenchuan Li, The First Clinical Medical College of Guangxi Medical University, Nanning 530021, Guangxi, China.
E-mail: 18477144235@163.com

Received: July 03, 2025 **Accepted:** September 15, 2025 **Published:** September 16, 2025

Cite this article: Li W. Personalized 3D-printed bone plates in fracture management: recent advances and future perspectives. BME Horiz. 2025;3:202512. <https://doi.org/10.70401/bmeh.2025.0005>

Abstract

This review examines recent advances and applications of three-dimensional (3D) printing technology in orthopedic fracture management, with a particular focus on its transformative role in personalized treatment strategies. The introduction of patient-specific 3D-printed implants and fracture plates has markedly improved surgical outcomes by reducing operative time, enhancing anatomical alignment, and promoting bone healing. By enabling the fabrication of customized implants, 3D printing provides an innovative approach for managing complex fractures and bone defects, particularly in cases where conventional methods are inadequate. Key benefits discussed include the development of tailored fracture plates, bone scaffolds, and bioactive materials that support bone regeneration. The review also explores the potential of emerging technologies such as four-dimensional printing and bioprinting, which allow for the creation of dynamic implants capable of adapting to biological changes and facilitating tissue regeneration. In addition, the integration of artificial intelligence into preoperative planning and implant design is highlighted for its contribution to improving surgical precision and individualized treatment. This review consolidates the latest advancements while also addressing challenges, including high production costs and regulatory barriers, that must be overcome for widespread clinical adoption. In conclusion, the future of orthopedic fracture management is expected to be significantly reshaped by the continuous evolution of 3D printing technologies, offering more personalized, effective, and efficient solutions for patients. As these innovations progress, 3D printing is anticipated to play a pivotal role in advancing orthopedic surgery and ultimately improving patient outcomes.

Keywords: 3D printing, patient-specific implants, customized fracture plates, 4D printing, bioprinting, additive manufacturing, smart implants

1. Introduction

Bone fractures are common injuries that affect individuals across all age groups and can substantially impair mobility and quality of life. The healing process of fractures involves complex physiological mechanisms, requiring the coordinated interaction of biological and mechanical factors to restore bone integrity. Typically, fracture healing progresses through three stages: the inflammatory phase, the reparative phase, and the remodeling phase. During this process, a blood clot forms at the fracture site, followed by the development of a soft callus, which subsequently mineralizes into hard bone. However, in some cases fractures fail to heal adequately, leading to complications such as delayed union, nonunion, or malunion^[1]. These challenges are particularly pronounced in elderly patients, where factors such as poor bone quality, comorbidities, and certain medications can impair the healing process. Given the growing demand for effective treatments, research into advanced methods of fracture repair has become increasingly important, with emerging technologies offering promising solutions.

Three-dimensional (3D) printing, also known as additive manufacturing, has emerged as a revolutionary technology with significant potential in medical applications, particularly in orthopedics. In fracture management, 3D printing enables the creation of patient-specific implants, scaffolds, and surgical tools that improve surgical outcomes. A key advantage of 3D printing lies in its ability to design and fabricate personalized solutions that accurately match the patient's anatomy. This is particularly valuable in the management of complex fractures involving irregular or non-standard bone geometries, which are difficult to address with conventional methods. The process employs a wide range of materials, including biocompatible polymers, metals, and bioceramics,



which can be incorporated into bone scaffolds to support regeneration and healing. Recent advances have further demonstrated the potential of 3D printing to produce customized bone grafts and implants that enhance recovery by promoting better integration with surrounding tissues^[2].

This review highlights recent advances in the application of 3D printing technologies for bone fracture repair, with a particular focus on individualized 3D-printed bone plates. The following sections examine the evolution of 3D printing in medicine, the integration of 3D-printed bone scaffolds in orthopedic trauma, and the key challenges and future directions of this technology. The potential of 3D printing to address critical issues, such as enhancing bone regeneration and enabling the design of more effective surgical interventions, is also discussed. Ultimately, this review aims to provide a comprehensive overview of how 3D printing is transforming fracture management and paving the way for more personalized and efficient therapeutic approaches^[3].

Bone fractures remain a major healthcare challenge, not only because of their high incidence but also due to the complexity of treatment and healing. The healing process involves callus formation at the fracture site, followed by bone remodeling, which is a highly intricate biological process. Despite advancements in treatment strategies, challenges persist, particularly in cases of complex fractures, fractures in elderly patients with reduced bone quality, and post-surgical complications such as infection or delayed union^[4]. Traditionally, fractures have been managed with external fixation, internal fixation, or casting. However, recent developments increasingly emphasize the role of 3D printing, which allows for the fabrication of patient-specific implants that more closely match both the anatomical and mechanical requirements of the fracture site^[5,6].

The use of 3D printing in orthopedic fracture management has gained significant momentum in recent years due to its ability to produce customized implants that improve the precision of fracture fixation. Traditional fixation methods, including metal plates, screws, and rods, are typically designed as one-size-fits-all solutions and may not provide an optimal fit, particularly in complex fractures. This limitation can result in nonunion, poor healing, or even implant failure^[7]. For example, although titanium and stainless steel are widely used in fracture fixation, studies have shown that they do not always provide ideal biomechanical properties for certain patient populations, especially those with osteoporosis^[8]. By applying 3D printing technology, implants can be designed to be both anatomically accurate and biomechanically optimized to meet the specific needs of the patient. Such tailored implants can markedly enhance fracture healing by improving load distribution and providing superior mechanical support at the fracture site^[9].

Computer-assisted surgical planning has further transformed modern surgery by enabling highly precise visualization and preoperative simulation. Using imaging technologies such as computed tomography (CT) and magnetic resonance imaging (MRI), spatial modeling of anatomical structures can be achieved, creating a three-dimensional framework for personalized procedures^[10]. When combined with 3D printing, this process is enhanced by the ability to fabricate patient-specific surgical guides, implants, and anatomical models, which significantly improve surgical accuracy and outcomes^[11].

The role of patient-specific implants in modern orthopedics has expanded beyond fracture fixation to applications in joint preservation and reconstruction. For instance, in the treatment of tibial plateau fractures, customized titanium implants have demonstrated promising outcomes by reducing complications and improving functional recovery^[12]. In addition, the development of advanced materials such as carbon fiber-reinforced polyether ether ketone (CFR-PEEK) provides notable advantages over conventional materials like stainless steel, offering superior biomechanical properties and a reduced risk of stress shielding^[9]. Incorporating CFR-PEEK into 3D-printed implants enables more flexible designs that closely mimic the mechanical behavior of natural bone, thereby providing both strength and a lower risk of implant failure.

Relevant studies for this review were identified through a comprehensive search of the PubMed database. The search was restricted to English-language articles published between 2020 and 2025. Eligible studies included original research articles, preclinical studies, clinical trials, and systematic reviews focusing specifically on the use of personalized 3D-printed bone plates in fracture management. Conference abstracts, case reports, editorials, and non-peer-reviewed publications were excluded. Additional references were obtained through manual screening of the bibliographies of key articles to ensure inclusion of the most relevant and up-to-date literature.

2. 3D Bioprinting Technology

3D printing has rapidly progressed from a niche manufacturing technique to a cornerstone of modern biomedical engineering. In recent years, its applications in medicine have extended beyond implant production to include prosthetics, surgical instruments, and drug delivery systems. Central to its success is the capacity to fabricate patient-specific, highly precise, and customizable medical devices, enhancing both treatment efficiency and clinical outcomes. One of the most prominent areas where 3D printing has made a significant impact is the development of personalized implants. By leveraging imaging modalities such as CT and MRI, clinicians can generate detailed, patient-specific anatomical models, which serve as the basis for producing implants tailored to the individual's unique skeletal structure. This ability to customize implants has transformed orthopedic surgery, particularly in complex scenarios involving fractures, joint replacements, and spinal procedures^[13,14].

The advent of 3D-printed implants offers several advantages over traditional manufacturing methods. In orthopedics, titanium and its

alloys have long been preferred due to their strength, biocompatibility, and corrosion resistance. 3D printing further enables the fabrication of intricate internal structures within titanium implants that replicate the porous architecture of bone, thereby enhancing osseointegration and reducing the risk of complications such as infection or implant failure^[15]. Moreover, 3D printing technologies, including Selective Laser Sintering and Fused Deposition Modeling, facilitate the creation of complex geometries that are unattainable with conventional manufacturing approaches^[16]. These technological advances have supported the successful integration of 3D-printed titanium implants in clinical practice, especially for customized prosthetics or implants designed to meet specific anatomical requirements^[17].

Beyond implants, 3D printing has also been widely applied to the production of surgical instruments and tools. A major advantage in this context is the ability to fabricate low-cost, patient-specific surgical instruments that streamline procedures and enhance precision. For instance, using 3D-printed surgical guides in joint replacement surgeries allows surgeons to achieve optimal implant positioning precisely aligned with the patient's anatomy^[18]. This personalized approach not only improves surgical outcomes but also mitigates risks associated with procedural errors, leading to faster recovery and reduced healthcare costs^[14]. Furthermore, the affordability and rapid production capabilities of 3D printing enable these tools to be manufactured quickly without the need for large-scale industrial facilities, enhancing accessibility in both resource-rich and resource-limited settings^[19].

The field of drug delivery has also greatly benefited from 3D printing technologies. By incorporating bioactive compounds into 3D-printed structures, researchers can design personalized drug delivery systems that target specific sites within the body. This approach is particularly advantageous for patients with chronic conditions or undergoing complex therapies, as it enables controlled and sustained drug release at precise dosages. 3D printing also facilitates the production of personalized tablets and capsules that release medications at predetermined times or in response to physiological triggers, representing a significant pharmacological advancement^[20]. Such tailored strategies improve treatment efficacy and patient compliance by aligning therapy with individual needs^[21].

In regenerative medicine, 3D printing is a powerful tool for fabricating tissue scaffolds that support tissue repair and regeneration. The development of biodegradable scaffolds, typically composed of natural polymers or composite materials known as bio-inks, is essential for promoting cell growth and guiding new tissue formation in vivo. These scaffolds are often designed to replicate the extracellular matrix, providing both mechanical support and biochemical signals necessary for cellular differentiation and tissue development. The ability to produce scaffolds with precise three-dimensional architectures using biocompatible materials creates new opportunities in tissue engineering, including the potential to print entire organs for transplantation^[15,22]. Although this field is still in its early stages, 3D bioprinting holds significant potential to transform regenerative medicine by enabling the creation of functional organs tailored to individual patient needs^[23]. [Table 1](#) summarizes the applications of 3D-printed bio-inks in fracture plates.

Table 1. Summary of bioink for 3D-printed bone plates.

Bioink Type	Advantages	Application Methods	References
Hydrogels (e.g., gelatin, alginate, collagen blends)	Biocompatible, mimic ECM, support cell viability, tunable porosity	Extrusion-based printing for scaffolds; cell-laden constructs for osteogenesis	[24]
Synthetic polymers (e.g., PLGA, PCL, PEG blends)	Tunable biodegradability, mechanical reinforcement, controlled drug release	Melt-extrusion 3D printing; combined with ceramics for hybrid plates	[25]
Ceramics (e.g., hydroxyapatite, tricalcium phosphate)	Excellent osteoconductivity, promote bone ingrowth, stiffness closer to cortical bone	Inkjet or extrusion printing; often combined with polymers/hydrogels for strength	[26,27]
Titanium alloys/metallic bioinks	High mechanical strength, durable under load, patient-specific contouring possible	SLM or electron beam melting; pre-contoured fracture plates	[28,29]

PLGA: poly(lactic-co-glycolic acid); PCL: polycaprolactone; PEG: poly (ethylene glycol); ECM: extracellular matrix; SLM: selective laser melting; 3D: three-dimension.

The role of 3D printing in healthcare is further expanding with the advent of four-dimensional (4D) printing, which incorporates time as an additional dimension. 4D printing employs smart materials that change shape in response to external stimuli such as heat, light, or moisture. This innovation has enabled new applications, including self-healing implants, adaptive stents, and drug delivery systems with release profiles that adjust according to environmental conditions^[17]. The development of materials that dynamically respond to the body's internal environment represents a major advance in personalized medicine, offering more tailored solutions to clinical challenges^[30].

3. Advances in Personalized 3D-Printed Bone Fracture Plates

The use of 3D printing for personalized bone fracture plates represents a major advancement in orthopedic surgery. Traditional bone

fixation plates, typically made from titanium or stainless steel, are usually pre-designed and often require intraoperative modifications to fit the patient's anatomy. This lack of customization can lead to complications such as delayed healing, non-union, or implant failure, particularly in complex fractures or in patients with unique anatomical characteristics^[31,32]. 3D printing enables the fabrication of implants tailored precisely to the patient's anatomy, enhancing the accuracy of fracture fixation and improving healing outcomes.

A key advantage of personalized 3D-printed fracture plates is that they can be designed based on preoperative imaging. This allows surgeons to plan procedures with greater precision, ensuring that the implant fits accurately and provides optimal support to the bone structure. This approach has been successfully applied in the management of complex fractures, such as tibial plateau fractures, where conventional methods often fall short. Evidence indicates that patient-specific, 3D-printed plates achieve better outcomes in terms of surgical time, blood loss, and postoperative recovery compared with traditional metal plates^[31]. Additionally, these implants can incorporate features such as internal porosity or bioactive coatings, which promote bone ingrowth and improve integration with surrounding tissue^[33].

Another significant advancement involves the development of bioactive 3D-printable materials that support bone healing and regeneration. Bioactive glasses and composite materials show considerable potential for enhancing the mechanical performance of plates while promoting osteointegration^[33,34]. These materials can be engineered to release growth factors or other biologically active agents that accelerate bone repair, thereby reducing the risk of complications such as non-union or infection^[31]. Furthermore, 3D printing enables the fabrication of complex geometries, including porous structures and lattice designs, which mimic the natural architecture of bone, improving both the mechanical properties of the plate and load distribution^[32,35]. [Table 2](#) summarizes the various materials used in 3D printing, along with their biomechanical characteristics and clinical outcomes.

Table 2. 3D-printed orthopedic implant materials.

Criteria	Titanium (Ti)	CFR-PEEK	Bioactive Composites (e.g., glass, ceramics)
Biomechanical Properties	• High stiffness and strength (Young's modulus ~110 GPa) • May cause stress shielding due to stiffness mismatch with bone • Good fatigue resistance	• Lower modulus (close to bone: 18-30 GPa) • Excellent fatigue and wear resistance • Radiolucent (CT/MRI compatible)	• Brittle but bioactive • Lower mechanical strength • Often used as coatings or fillers, not load-bearing cores
Adhesion/Osseointegration	• Excellent osseointegration, especially with nnHA coatings • Surface roughness and porosity improve bonding	• Inert surface; poor osseointegration without surface modification • Needs coating (e.g., HA, titanium) or bioactive fillers	• Strong bone-bonding ability due to chemical similarity to natural bone minerals • Stimulates osteoblast adhesion and proliferation
Surgical Time	• Standard surgical protocols well-developed • 3D-printed personalized implants may reduce surgical adjustment time	• Similar to titanium • Preoperative customization may reduce intraoperative handling	• Typically used as granules or coatings, so short surgical time • Not usually shaped for structural load-bearing
Risk of Failure	• Risk of failure due to stress shielding and infection • Possible loosening over time if not well integrated	• Lower stress shielding risk than titanium • Surface bio-inertness can lead to fibrous encapsulation (if not modified)	• Brittle, so prone to fracture if used structurally • However, low risk biologically and good long-term integration
References	[36,37]	[38-40]	[33,41]

CFR-PEEK: carbon fiber-reinforced polymer; CT: computed tomography; MRI: magnetic resonance imaging; nnHA: nano-needle hydroxyapatite; 3D: three-dimension.

The integration of 3D printing with other technologies, such as augmented reality (AR) and virtual surgical planning (VSP), further enhances the precision and effectiveness of fracture fixation. AR systems that incorporate 3D-printed plates assist surgeons in visualizing the optimal placement and alignment of implants during surgery. This approach has been shown to improve surgical

accuracy, reduce operative time, and minimize the risk of errors^[42]. Additionally, VSP allows for detailed preoperative simulations, enabling surgeons to anticipate challenges and customize implants to fit the exact contours of the bone, thereby improving outcomes in complex surgical cases^[32].

In addition to the clinical benefits, personalized 3D-printed plates offer significant economic advantages. The bulk production of traditional metal plates often results in implant-anatomy mismatches, which may necessitate costly revisions or additional surgeries. In contrast, 3D printing enables on-demand production of customized implants, reducing the need for extensive inventories and potentially lowering overall healthcare costs. Studies indicate that personalized implants can lead to shorter hospital stays, fewer complications, and improved functional outcomes, all of which contribute to long-term cost savings^[43].

4. Clinical Applications and Case Studies

The clinical applications of personalized 3D-printed bone fracture plates are expanding rapidly, providing tailored solutions for complex fractures that are difficult to address with traditional methods. A major advantage of 3D printing in orthopedic surgery is its ability to produce patient-specific implants, which improve surgical precision and outcomes, particularly for patients with anatomical variations or complex fractures. One notable example is the use of this technology in tibial plateau fractures, where conventional plates often fail to achieve adequate fixation. In a study by Duan *et al.*, 3D-printed plates designed using preoperative CT scans resulted in reduced intraoperative blood loss, shorter surgical time, and improved knee joint function at six-month and one-year follow-ups compared with traditional plates^[34].

Similarly, 3D printing has shown promising results in the preoperative planning and surgical management of acetabular fractures. In a study by Papotto *et al.*^[29], 3D-printed models were employed for preoperative planning in patients with complex acetabular fractures. The use of these models enabled more accurate fracture reduction and fixation, reduced the number of intraoperative fluoroscopies, and improved functional outcomes. This approach was associated with shorter operative times, lower blood loss, and fewer complications compared to conventional methods^[29]. These cases highlight the precision and efficiency benefits of 3D-printed implants, demonstrating their value in managing complex fractures.

3D printing has also been applied in upper extremity surgery, where fractures of the humerus or scaphoid can be particularly challenging. Bodansky *et al.* investigated the application of 3D technology in upper extremity fractures, showing that it has transformed both surgical planning and treatment, especially in cases of malunion or nonunion. One innovative case involved a 3D-printed customized plate for a scaphoid fracture nonunion^[44]. Using a preoperative 3D model to guide implant positioning allowed for more accurate fracture alignment, improving postoperative carpal biomechanics and reducing complications associated with nonunion^[45,46].

The benefits of 3D printing are also evident in the reconstruction of large bone defects following tumor resections. Shao *et al.* reported a case series in which 3D-printed prostheses were used to reconstruct femoral bone defects after tumor removal. These customized intercalary prostheses were designed to match the patients' unique bone geometry, enabling joint-preserving surgeries and restoring function without requiring more invasive joint replacement procedures^[47]. This approach led to significant improvements in postoperative recovery and functional outcomes compared with traditional prosthetic replacements, particularly in cases with limited cortical bone^[47]. Such applications demonstrate that 3D printing can extend beyond fracture fixation to more complex reconstructions, offering personalized solutions that conventional methods cannot achieve.

The integration of AR with 3D printing represents another advanced development in surgical practice. Guo *et al.* applied AR-assisted surgery in the treatment of scapular fractures, combining 3D-printed fracture plates with virtual reality guidance for the procedure^[42]. This innovative method enhanced the accuracy of plate placement, reduced operative time, and minimized blood loss. The use of AR alongside 3D-printed implants marks a significant advancement in orthopedic surgery, particularly for complex and high-risk fractures.

In summary, the clinical applications of personalized 3D-printed bone fracture plates are extensive, ranging from routine fractures to complex reconstructions and tumor resections (Table 3). The technology provides more precise, efficient, and safer surgical options, improving patient outcomes while reducing the risks associated with conventional methods. As 3D printing continues to evolve, its integration with complementary technologies such as AR will further expand the potential for personalized and minimally invasive treatments for complex fractures and bone defects.

Table 3. Clinical cases.

Author	Year	Type of Fracture	Material	Clinical Outcome
Chovanec <i>et al.</i> ^[48]	2024	Complex fractures (general review)	Titanium, polymers, ceramics, hydrogels	Improved pre-op planning, precision, reduced operative time, challenges in clinical integration

Robinson <i>et al.</i> ^[49]	2023	Pelvic acetabular fractures (cadaveric)	Ti6Al4V (3D-printed plates via SLM)	Manufacturing feasible; accuracy issues with > 6 fragments; need for alignment guides
Xiong <i>et al.</i> ^[50]	2023	Olecranon fractures (Mayo II)	3D-printed navigation template for K-wires	Higher bicortical placement success (85.7% vs 60%); reduced fluoroscopy; fewer complications
Ivanov <i>et al.</i> ^[51]	2022	Complex acetabular fractures	3D-printed pre-op models (PLA) + titanium plates	Reduced blood loss, operative time, x-rays; better reduction (80% good vs 50% in controls); improved function
Rao <i>et al.</i> ^[52]	2023	Upper extremity fractures (distal radius, ulna)	Patient-specific 3D-printed guides & implants	Reduced OR time, blood loss, fluoroscopy; higher patient satisfaction; case reports show pain-free recovery
Papotto <i>et al.</i> ^[29]	2022	Acetabular fractures (systematic review of RCTs)	Pre-contoured titanium plates via 3D printing	Reduced surgery time, blood loss, better fracture reduction (< 2 mm displacement more frequent); fewer complications

3D: three-dimension; RCT: Randomized controlled trials; PLA: polylactic acid.

5. Future Directions

As 3D printing continues to advance in personalized medicine, particularly in orthopedic and fracture management, its future potential is extensive and promising. One of the most exciting directions is the integration of AI and machine learning with 3D printing. AI can optimize the design process by analyzing large datasets of patient-specific anatomical information, enabling the creation of increasingly refined and customized implants. AI-assisted 3D preoperative planning has shown notable improvements in surgical accuracy. For example, Wu *et al.* reported that in total hip arthroplasty, this approach achieved higher success rates in prosthesis size prediction compared with conventional 2D X-ray templating, with significantly improved matching accuracy^[53]. This technology is expected to evolve further, incorporating predictive analytics in which machine learning algorithms anticipate potential complications and recommend optimal implant designs based on a patient's medical history, thereby enhancing both quality of life and postoperative outcomes^[54].

Another promising avenue is 4D printing, in which materials respond to external stimuli such as temperature or pH changes. This approach enables dynamic implants that adjust over time to better align with the biological environment. 4D printing has particular potential in tissue engineering and regenerative medicine. For instance, 4D-printed scaffolds could adapt to the mechanical and biochemical requirements of healing bone, promoting superior integration and tissue regeneration compared with conventional static implants^[55]. The development of 4D-printed bone scaffolds could significantly improve outcomes in the treatment of complex fractures by allowing the implants to modify their shape and mechanical properties in response to bone healing^[56].

Beyond material advancements, bioprinting is expected to play a transformative role in the future of 3D-printed medical devices, particularly in the development of biocompatible implants and tissue engineering. Future innovations may include bioprinted bone grafts incorporating living cells and growth factors, which could accelerate and enhance bone regeneration. Such advances have the potential to significantly improve outcomes for patients with severe bone defects or those requiring extensive reconstructive procedures^[57]. Additionally, continued progress in bioprinting techniques may enable the production of functional organs for transplantation, offering a promising solution to organ shortages^[58].

In spinal surgery, the use of customized titanium spinal implants produced by 3D printing shows considerable promise, especially for complex procedures such as spinal fusion. Future research is likely to focus on combining these personalized implants with biomechanical modeling to optimize their mechanical strength and stability. Smart implants capable of monitoring the healing process and providing real-time data to clinicians may become a standard feature of personalized medical solutions, enabling more precise and effective treatments^[59].

Finally, cost-effectiveness and regulatory considerations will remain important factors in the broader adoption of 3D-printed medical devices. Despite the potential for more personalized and efficient treatments, widespread implementation is often limited by high initial costs and the slow pace of regulatory approval. Efforts to standardize 3D printing processes, together with advances in material sourcing and scalable production, are expected to improve accessibility and affordability, ultimately reducing healthcare costs while enhancing patient care^[60].

6. Conclusion

The integration of 3D printing technology into orthopedic fracture management represents a significant advancement in personalized medicine. Currently, leading clinical applications involve 3D-printed titanium and CFR-PEEK implants, which provide superior mechanical properties and improved biomechanical compatibility compared with traditional metal plates. These technologies enable the production of patient-specific implants and fracture plates, enhancing surgical precision and clinical outcomes. Titanium-based 3D-printed implants remain the most widely used in clinical practice. Numerous studies have demonstrated that 3D-printed bone fracture plates offer advantages over conventional methods, including reduced surgical time, lower intraoperative blood loss, and improved bone healing, particularly in complex fractures and bone defects^[31,32]. The ability to tailor implants to the patient's specific anatomy, together with the incorporation of bioactive materials that promote bone integration, represents a major step forward in personalized fracture care.

Looking ahead, the role of 3D printing in orthopedic surgery is expected to continue evolving, driven by advances in material science, bioprinting, and artificial intelligence. Emerging technologies such as 4D printing and bioprinting have the potential to transform the treatment of bone fractures. For example, 4D-printed and bioprinted scaffolds could facilitate bone regeneration and repair, offering solutions for large bone defects and complex fractures that are not achievable with traditional methods^[55,58]. In addition, AI-assisted preoperative planning and smart implants capable of monitoring the healing process will provide clinicians with enhanced tools to optimize treatment outcomes^[54]. Nevertheless, challenges remain, including high production costs and regulatory barriers, which must be addressed to enable broader adoption and ensure the continued success of 3D printing in orthopedic surgery.

In summary, advances in 3D printing technology have the potential to transform orthopedic care by providing customized solutions that enhance the precision, effectiveness, and safety of fracture treatments. The integration of artificial intelligence, bioprinting, and advanced materials is expected to further expand the clinical applications of 3D printing, supporting more patient-centered approaches in orthopedic surgery. As these technologies continue to evolve, 3D printing is likely to become an integral component of orthopedic practice, improving patient outcomes and reducing the overall burden on healthcare systems.

Declarations

Authors contribution

The author contributed solely to the article.

Conflicts of interest

The author declares no competing interests.

Ethical approval

Not applicable.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

Not applicable.

Funding

None.

Copyright

© The Author(s) 2025.

References

1. Bizzoca D, Vicenti G, Caiaffa V, Abate A, De Carolis O, Carrozzo M, et al. Assessment of fracture healing in orthopaedic trauma. *Injury*. 2023;54:S46-S52. [DOI]
2. González-Alonso M, Hermida-Sánchez M, Martínez-Seijas P, Ruano-Ravina A. Application of 3D printing in the treatment of appendicular

- skeleton fractures: systematic review and meta-analysis. *J Orthop Res.* 2021;39(10):2083-2092. [DOI]
3. Hecker A, Tax L, Giese B, Schellnegger M, Pignet AL, Reinbacher P, et al. Clinical applications of three-dimensional printing in upper extremity surgery: a systematic review. *J Pers Med.* 2023;13(2):294. [DOI]
 4. Bihari A, Gee A, Bougherara H, Brzozowski P, Lawendy AR, Schemitsch EH, et al. Cytotoxicity of novel hybrid composite materials for making bone fracture plates. *Biomed Mater.* 2024;19(4):041001. [DOI]
 5. Choi JH, Lee JH, Lee SH, Jang WY. Clinical efficacy of three-dimensional-printed pure titanium fracture plates with locking screw systems in distal tibia fractures. *Medicina.* 2025;61(1):137. [DOI]
 6. Ali M, Elamin D, Ibrahim A, Mannan SS. Distal radius plates with coracoid suture anchors for the fixation of displaced lateral end clavicle fractures. *Cureus.* 2023;15(12):e50720. [DOI]
 7. Bhashyam AR, Yeung C, Sodhi A, Xu RF, Groot OQ, Kelly S, et al. Titanium vs. carbon fiber-reinforced intramedullary nailing for humeral bone tumors. *J Shoulder Elbow Surg.* 2023;32(11):2286-2295. [DOI]
 8. Barber CC, Burnham M, Ojameruaye O, McKee MD. A systematic review of the use of titanium versus stainless steel implants for fracture fixation. *OTA Int.* 2021;4(3):e138. [DOI]
 9. Giannoudis VP, Rodham P, Antypas A, Mofori N, Chloros G, Giannoudis PV. Patient perspective on the use of carbon fibre plates for extremity fracture fixation. *Eur J Orthop Surg Traumatol.* 2023;33(6):2573-2577. [DOI]
 10. Zhang D, Bauer AS, Blazar P, Earp BE. Three-dimensional printing in hand surgery. *J Hand Surg Am.* 2021;46(11):1016-1022. [DOI]
 11. Brachet A, Bežek A, Furtak D, Geworgjan Z, Tulej D, et al. Application of 3D printing in bone grafts. *Cells.* 2023;12(6):859. [DOI]
 12. Hu Z, Ren W, Zhang W, Li L, Xu W. Potential problem and solution of lateral plate postposition for the posterolateral tibial plateau fracture. *J Orthop Surg Res.* 2023;18(1):984. [DOI]
 13. Liang W, Zhou C, Zhang H, Bai J, Jiang B, Jiang C, et al. Recent advances in 3D printing of biodegradable metals for orthopaedic applications. *J Biol Eng.* 2023;17(1):56. [DOI]
 14. Kotrych D, Angelini A, Bohatyrewicz A, Ruggieri P. 3D printing for patient-specific implants in musculoskeletal oncology. *EFORT Open Rev.* 2023;8(5):331-339. [DOI]
 15. Freeman FE, Burdis R, Kelly DJ. Printing new bones: from print-and-implant devices to bioprinted bone organ precursors. *Trends Mol Med.* 2021;27(7):700-711. [DOI]
 16. Grygier D, Kujawa M, Kowalewski P. Deposition of biocompatible polymers by 3D printing (FDM) on titanium alloy. *Polymers.* 2022;14(2):235. [DOI]
 17. Li N, Khan SB, Chen S, Aiyiti W, Zhou J, Lu B. Promising new horizons in medicine: Medical advancements with nanocomposite manufacturing via 3D printing. *Polymers.* 2023;5(20):4122. [DOI]
 18. Kamel MK, Cheng A, Vaughan B, Stiles B, Altorki N, Spector JA, et al. Sternal reconstruction using customized 3D-printed titanium implants. *Ann Thorac Surg.* 2020;109(6):e411-e444. [DOI]
 19. Alzoubi L, Aljabali AA, Tambuwala MM. Empowering precision medicine: the impact of 3D printing on personalized therapeutic. *Aaps Pharmscitech.* 2023;24(8):228. [DOI]
 20. Agarwal P, Arora G, Panwar A, Mathur V, Srinivasan V, Pandita D, et al. Diverse applications of three-dimensional printing in biomedical engineering: a review. *3D Print Addit Manuf.* 2023;10(5):1140-1163. [DOI]
 21. Khan MS, Khan SA, Shabbir S, Umar M, Mohapatra S, Khuroo T, et al. Raw materials, technology, healthcare applications, patent repository and clinical trials on 4D printing technology: an updated review. *Pharmaceutics.* 2022;15(1):116. [DOI]
 22. Arif ZU, Khalid MY, Noroozi R, Hossain M, Shi HH, Tariq A, et al. Additive manufacturing of sustainable biomaterials for biomedical applications. *Asian J Pharm Sci.* 2023;18(3):100812. [DOI]
 23. Kantaros A. 3D printing in regenerative medicine: technologies and resources utilized. *Int J Mol Sci.* 2022;23(23):14621. [DOI]
 24. Zhang C, Shi T, Wu D, Hu D, Li W, Fei J, et al. The application of three-dimensional-printed hydrogels in bone tissue engineering. *Tissue Eng Part B Rev.* 2024;30(5):492-506. [DOI]
 25. Gharibshahian M, Salehi M, Beheshtizadeh N, Kamalabadi-Farahani M, Atashi A, Nourbakhsh MS, et al. Recent advances on 3D-printed PCL-based composite scaffolds for bone tissue engineering. *Front Bioeng Biotechnol.* 2023;11:1168504. [DOI]
 26. Li Y, Jahr H, Zhou J, Zadpoor AA. Additively manufactured biodegradable porous metals. *Acta Biomater.* 2020;115:29-50. [DOI]
 27. Feng Y, Zhu S, Mei D, Li J, Zhang J, Yang S, et al. Application of 3D printing technology in bone tissue engineering: a review. *Curr Drug Deliv.* 2021;18(7):847-861. [DOI]
 28. Papotto G, Testa G, Mobilia G, Perez S, Dimartino S, Giardina SM, et al. Use of 3D printing and pre-contouring plate in the surgical planning of acetabular fractures: a systematic review. *Orthop Traumatol Surg Res.* 2022;108(2):103111. [DOI]
 29. Chen Y, Li W, Zhang C, Wu Z, Liu J. Recent developments of biomaterials for additive manufacturing of bone scaffolds. *Adv Healthc Mater.* 2020;9(23):2000724. [DOI]
 30. Khan SB, Irfan S, Zhang Z, Yuan W. Redefining medical applications with safe and sustainable 3D printing. *ACS Appl Bio Mater.* 2025;8(8):6470-6525. [DOI]
 31. Duan S, Xu R, Liang H, Sun M, Liu H, Zhou X, et al. Study on the efficacy of 3D printing technology combined with customized plates for the treatment of complex tibial plateau fractures. *J Orthop Surg Res.* 2024;19(1):562. [DOI]
 32. Mendonça CJ, Gasoto SC, Belo IM, Setti JA, Soni JF, Schneider B. Application of 3D printing technology in the treatment of Hoffa's fracture nonunion. *Rev Bras Ortop.* 2023;58(2):303-312. [DOI]
 33. Dukle A, Murugan D, Nathanael AJ, Rangasamy L, Oh TH. Can 3D-printed bioactive glasses be the future of bone tissue engineering?

- Polymers. 2022;14(8):1627. [DOI]
34. Chen C, Huang B, Liu Y, Liu F, Lee IS. Functional engineering strategies of 3D printed implants for hard tissue replacement. *Regen Biomater.* 2023;10:rbac094. [DOI]
35. Ferre LS, Di Nisio FG, Mendonça CJ, Belo IM. Comparative analysis of tibial plateau fracture osteosynthesis: a finite element study. *J Mech Behav Biomed Mater.* 2022;134:105392. [DOI]
36. Li Y, Li H, Lai Q, Xue R, Zhu K, Deng Y. Finite element analysis of 3D-printed personalized titanium plates for mandibular angle fracture. *Comput Methods Biomech Biomed Engin.* 2023;26(1):78-89. [DOI]
37. Man K, Brunet MY, Louth S, Robinson TE, Fernandez-Rhodes M, Williams S, et al. Development of a bone-mimetic 3D printed Ti6Al4V scaffold to enhance osteoblast-derived extracellular vesicles' therapeutic efficacy for bone regeneration. *Front Bioeng Biotechnol.* 2021;9:757220. [DOI]
38. Wang Y, Ulbricht A, Schmidt F, Müller BR, Kupsch A, Schwitalla AD. Micro-CT analysis and mechanical properties of low dimensional CFR-PEEK specimens additively manufactured by material extrusion. *J Mech Behav Biomed Mater.* 2023;146:106085. [DOI]
39. Hanemann T, Klein A, Baumgärtner S, Jung J, Wilhelm D, Antusch S. Material extrusion 3D printing of PEEK-based composites. *Polymers.* 2023;15(16):3412. [DOI]
40. Chen J, Cao G, Li L, Cai Q, Dunne N, Li X. Modification of polyether ether ketone for the repairing of bone defects. *Biomed Mater.* 2022;17(4):042001. [DOI]
41. Lin H, Zhang L, Zhang Q, Wang Q, Wang X, Yan G. Mechanism and application of 3D-printed degradable bioceramic scaffolds for bone repair. *Biomater Sci.* 2023;11(21):7034-7050. [DOI]
42. Guo Q, Li X, Tang Y, Huang Y, Luo L. Augmented reality and three-dimensional plate library-assisted posterior minimally invasive surgery for scapula fracture. *Int Orthop.* 2022;46(4):875-882. [DOI]
43. Brouwer de Koning SG, de Winter N, Moosabeiki V, Mirzaali MJ, Berenschot A, Witbreuk MM, et al. Design considerations for patient-specific bone fixation plates: a literature review. *Med Biol Eng Comput.* 2023;61(12):3233-3252. [DOI]
44. Bodansky DM, Sandow MJ, Volk I, Luria S, Verstreken F, Horwitz MD. Insights and trends review: the role of three-dimensional technology in upper extremity surgery. *J Hand Surg.* 2023;48(5):383-395. [DOI]
45. Li LX, Kedgley AE, Horwitz MD. A review of the use of 3D printing technology in treatment of scaphoid fractures. *J Hand Surg.* 2023;28(1):22-33. [DOI]
46. Oki S, Matsuo T, Furuhashi R, Iwabu S. Scaphoid non-union with pre-existing screws treated by 3D preoperative planning. *BMJ Case Rep.* 2021;14(1):e239548. [DOI]
47. Shao X, Dou M, Yang Q, Li J, Zhang A, Yao Y, et al. Reconstruction of massive bone defects after femoral tumor resection using two new-designed 3D-printed intercalary prostheses: a clinical analytic study with the cooperative utilization of multiple technologies. *BMC Musculoskelet Disord.* 2023;24(1):67. [DOI]
48. Chovanec M, Krtička M, Šrámek J, Kovařík J. Current clinical applications of 3D printing in the management of complex fractures. *Rozhl Chir.* 2024;103(5):158-166. [DOI]
49. Robinson DL, Bucknill A, Ferragina A, Campbell C, Lee PV. Fixation of pelvic acetabular fractures using 3D-printed fracture plates: a cadaver study. *J Orthop Surg Res.* 2023;18(1):360. [DOI]
50. Xiong X, Chen YL, Zhao L, Li H, Xu M, Shuang F. Individualized 3D-printed navigation template-assisted tension band wiring for olecranon fractures. *J Orthop Surg Res.* 2023;18(1):407. [DOI]
51. Ivanov S, Valchanov P, Hristov S, Veselinov D, Gueorguiev B. Management of complex acetabular fractures by using 3D printed models. *Medicina.* 2022;58(12):1854. [DOI]
52. Rao SR, Pereira GF, Richard MJ. The use of patient-specific implants for the treatment of upper extremity fractures. *Hand Clin.* 2023;39(4):489-503. [DOI]
53. Wu L, Yang XC, Wu J, Zhao X, Lu ZD, Li P. Short-term outcome of artificial intelligence-assisted preoperative three-dimensional planning of total hip arthroplasty for developmental dysplasia of the hip compared to traditional surgery. *Jt Dis Relat Surg.* 2023;34(3):571-582. [DOI]
54. Wang J, Zhao Z, Liang H, Zhang R, Liu X, Zhang J, et al. Artificial intelligence assisted preoperative planning and 3D-printing guiding frame for percutaneous screw reconstruction in periacetabular metastatic cancer patients. *Front Bioeng Biotechnol.* 2024;12:1404937. [DOI]
55. Chen M, Gao M, Bai L, Zheng H, Qi HJ, Zhou K. Recent advances in 4D printing of liquid crystal elastomers. *Adv Mater.* 2023;35(23):2209566. [DOI]
56. Amaya-Rivas JL, Perero BS, Helguero CG, Hurel JL, Peralta JM, Flores FA, et al. Future trends of additive manufacturing in medical applications: an overview. *Heliyon.* 2024;10(5):e26641. [DOI]
57. Zhang Q, Zhou J, Zhi P, Liu L, Liu C, Fang A, et al. 3D printing method for bone tissue engineering scaffold. *Med Nov Technol Devices.* 2023;17:100205. [DOI]
58. Jovic TH, Combella EJ, Jessop ZM, Whitaker IS. 3D bioprinting and the future of surgery. *Front Surg.* 2020;7:609836. [DOI]
59. Lewandrowski KU, Vira S, Elfar JC, Lorio MP. Advancements in custom 3D-printed titanium interbody spinal fusion cages and their relevance in personalized spine care. *J Pers Med.* 2024;14(8):809. [DOI]
60. Prakash A, Malviya R, Singh DP. Transformative potential and healthcare applications of 3D printing. *Curr Pharm Des.* 2024;30(42):3311-3321. [DOI]

Publisher's Note

Science Exploration remains a neutral stance on jurisdictional claims in published maps and institutional affiliations. The views expressed in this article are solely those of the author(s) and do not reflect the opinions of the Editors or the publisher.