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Application Progress of 3D Printing in Orthopedic Clinical Practice

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Abstract: In recent years, 3D printing technology has been widely applied in the field of orthopedics, covering preoperative planning, surgical simulation, personalized implants, and surgical guides, all demonstrating broad application prospects. This article systematically elaborates on the basic principles, methods, and materials of 3D printing technology, as well as its current application status, technological progress, and clinical effects in orthopedics. It also briefly outlines future directions such as artificial intelligence-assisted design and bio-printing. In the future, the combination of 3D printing and artificial intelligence will further reduce printing costs and simplify clinical operation procedures, enabling more patients to benefit from personalized and precise treatments. This will become an important direction for the next stage of orthopedic research.

Keywords: 3D printing; Model; Personalized implant; Surgical guide; Orthosis

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1. Introduction

Orthopedic diseases encompass various types such as trauma, degeneration, tumors, and congenital deformities. Traditional orthopedic surgeries mainly rely on standardized implants, intraoperative fluoroscopy, and the surgeon's experience. When dealing with complex anatomical structures, severe deformities, and large-scale bone defects, these surgeries often encounter problems such as poor matching of implants, inaccurate mechanical axis reconstruction, prolonged operative time, and significant radiation exposure. 3D printing technology, with its advantages of personalized design, has become an important innovative force in the field of orthopedics. From anatomical models, surgical guides to customized implants and orthoses, 3D printing is changing the paradigm of orthopedic diagnosis and treatment. This article reviews the current progress of 3D printing technology in clinical orthopedic treatment as follows.

2. Methods and materials

2.1. Definition and basic principles of 3D printing

3D printing, also known as Additive Manufacturing (AM), is an advanced manufacturing technology that creates physical parts by layering materials on top of each other based on three-dimensional computer-aided design (CAD) data. Its core workflow involves creating a three-dimensional digital model of an object using computer-aided design software or medical imaging data (such as DICOM files from CT or MRI scans), which can include complex internal structures and detailed external shapes. Then, using slicing software, the three-dimensional model will be divided into a series of extremely thin two-dimensional slices (typically ranging from several tens to several hundred micrometers), with each slice representing the cross-sectional contour at that height. The slicing software simultaneously generates detailed printing paths and device instructions. Finally, the 3D printer will build the solid model by stacking materials layer by layer based on these two-dimensional data.

2.2. Methods of 3D printing

Table 1. Methods, advantages and limitations of 3D printing technologies [1]

3D printing technology	Methods	Advantages	Limitations
Stereolithography apparatus (SLA) & Digital light processing (DLP)	Both technologies use liquid photopolymer resin as the raw material. SLA cures the resin by scanning point by point with an ultraviolet laser beam in a layer-by-layer manner. DLP, a derivative technology of SLA, projects an entire layer image onto the resin surface at once using a digital light projector.	Extremely high resolution, smooth surface	Limited mechanical strength, relatively long printing time
Fused deposition modeling (FDM)	This technology uses a heated nozzle to melt and extrude thermoplastic filaments, which are then deposited layer by layer along a predefined path and solidified upon deposition.	Low equipment cost, easy to operate, a wide variety of available materials	Relatively low forming accuracy, visible layer lines on the surface, require post-processing
Selective laser sintering / Selective laser melting (SLS/SLM) & Electron beam melting (EBM)	SLS uses a laser to selectively sinter polymer or ceramic powders. SLM and EBM fully melt metal powders using a high-energy laser beam or electron beam.	No need for support structures, recyclability of unused powder, a wide range of applicable materials	High equipment cost, relatively long printing time, rough surface
Direct ink writing (DIW)	DIW extrudes viscoelastic inks—such as hydrogels, ceramic slurries, and biomacromolecules—through a micron-scale nozzle using pneumatic pressure or mechanical force, and builds up layer by layer to form a structure.	Avoid heat-induced damage to bioactive materials by printing at room temperature, possess excellent biocompatibility and biodegradability	Relatively poor mechanical strength, require post-processing to maintain structural integrity, require stringent printing conditions to preserve cell viability
Three-dimensional printing (3DP) & material jetting	3DP selectively ejects a binder through a nozzle to fuse powder materials into a shape. Material Jetting, directly jets droplets of photopolymer resin, and they are instantly cured by ultraviolet light.	Require no support structures, fast printing speed	The accuracy and surface quality will be influenced by factors such as powder particle size, relatively low mechanical strength

2.3. Materials for 3D printing

Table 2. Advantages, limitations and orthopedic applications of different 3D printing materials [1]

Material	Advantages	Limitations	Orthopedic applications
Metal	High strength, high hardness, wear resistance, corrosion resistance, good biocompatibility	Require post-processing, excessively high elastic modulus led to stress shielding	Load-bearing implants, porous structures can reduce the elastic modulus and promote osseointegration
Polymer	Good plasticity and processability, elastic modulus close to that of bone, radiolucency, easy to print, low cost, high accuracy	Low strength, non-osteogenic	Models, catheters, implants, bone repair scaffolds, drug delivery
Ceramic	Excellent bioactivity and osteoconductive, wear resistance, promote bone growth	High brittleness, require high-temperature processing, require polishing	Bone defect treatment, bone grafting, coatings, joint surface
Bioink	Excellent biocompatibility, biodegradability	Low mechanical strength, regulatory hurdles	Cartilage and bone tissue construction, enhancement of osteogenesis, regenerative scaffolds, active repair, anti-infection functionality

3. Clinical applications of 3D printing

3D printing technology can be used for preoperative planning, surgical simulation, and the design of personalized implants and surgical guides. In the treatment of complex fractures, 3D-printed models can be used for preoperative planning and simulation, assisting surgeons in intuitively understanding the morphology of complex fractures, simulating osteotomy and reduction, and significantly shortening operative time while reducing blood loss. In addition, 3D-printed implants can be used to repair bone defects in patients, while the application of 3D-printed guides can improve the accuracy of implant placement and reduce the frequency of intraoperative fluoroscopy. In summary, 3D printing technology has demonstrated significant advantages in fields such as spinal surgery, complex fracture management, and joint arthroplasty [2].

3.1. Spinal surgery

In the field of spinal surgery, the use of 3D printing has grown significantly, and its potential benefits have attracted widespread attention. It offers advantages such as improved surgical accuracy, better treatment outcomes, shortened operative time, and reduced blood loss and ionizing radiation exposure [3]. Compared with traditional methods, it lowers the risk of surgical complications such as nerve injury, ultimately improving patients' overall quality of life. 3D-printed porous titanium alloy cervical cages and artificial vertebral bodies are used in the treatment of spinal degeneration, tumors, and deformity correction. Their porous structure can promote early osseointegration while reducing subsidence and migration [4]. Representative examples of guide-assisted spinal surgeries in clinical practice include spinal fusion and spinal deformity correction. The use of 3D printing-assisted cervical pedicle screw internal fixation has demonstrated advantages such as reduced surgical trauma and blood loss during the procedure, effectively restoring cervical stability and promoting spinal fusion [5]. A study involving 60 cases of cervical screw placement confirmed the significant superiority of 3D-printed guides, showing that they can shorten screw placement time, improve accuracy and safety, and lead to better recovery of cervical function [6]. In congenital scoliosis, 3D-printed full-spine models can visually present the curvature angle, vertebral rotation, and vertebral developmental abnormalities. They enable accurate measurement of the Cobb angle, pedicle width, and pedicle channel, as well as preoperative simulation of osteotomy, fusion levels, and correction angles. During surgery, they facilitate the safe and relatively rapid placement of foundation screws, thereby achieving better treatment outcomes [7].

3.2. Trauma orthopedics

In trauma orthopedics, 3D printing is primarily used for the treatment of challenging intra-articular fractures, complex diaphyseal fractures, and malunited fractures. 3D-printed fracture models can reproduce articular surface collapse and fracture fragment displacement, and are used preoperatively to simulate reduction and pre-bend plates to match the patient's anatomical curvature. During surgery, personalized 3D-printed guides can be used to achieve minimally invasive fixation. This technology can significantly shorten operative time, reduce blood loss, improve the accuracy of articular surface reduction, minimize soft tissue damage, lower the incidence of postoperative post-traumatic arthritis, enhance the fit of internal fixation, and lead to better functional recovery [8].

In the context of the hip joint and pelvis, 3D-printed models can enhance understanding of acetabular fracture morphology, thereby facilitating the determination of the optimal surgical approach, reduction technique, and the positioning and fixation of implants. Additionally, 3D-printed guides assist in percutaneous screw placement, improving screw placement accuracy [9]. Furthermore, studies have shown that 3D printing-assisted surgery not only reduces intraoperative blood loss and operative time in pelvic fracture surgery, but also improves the reduction quality of comminuted and complex fractures [10]. For fractures such as tibial plateau fractures, acetabular fractures, pelvic fractures, and spinal fractures, the accuracy of fracture reduction is significantly enhanced, achieving precise implantation and improved outcomes [11].

Meanwhile, the integration of 3D printing technology with robot-assisted surgery has opened new frontiers in orthopedic surgery. By creating patient-specific anatomical models and preoperative planning tools, 3D printing enables a higher degree of customization, ensuring that the surgical approach aligns with the patient's unique anatomy. Combined with the high precision of robotic systems, this approach significantly improves screw placement accuracy, shortens operative time, and reduces surgical complications and intraoperative radiation exposure [12].

3.3. Joint surgery

In joint revision surgery, accurate assessment of bone defects is critical for selecting the appropriate reconstruction method. 3D-printed models can visually present the morphology, extent, and relationship of bone defects to critical anatomical structures, providing a basis for selecting impaction bone grafting, metal augments, or customized prostheses. In ankle arthrodesis for the treatment of end-stage ankle arthritis, 3D printing enables the customization of fusion cages or locking plates that match the morphology of the distal tibia and talus, thereby improving the fusion rate and the accuracy of mechanical axis reconstruction [13]. For bone defects around the shoulder and elbow joints, such as humeral head necrosis and post-traumatic arthritis of the elbow, 3D printing allows for the customization of prosthetic humeral heads, glenoid augments, or elbow prostheses to achieve anatomical reconstruction.

In total hip arthroplasty (THA), the anteversion and abduction angles of the acetabular prosthesis, as well as the rotational alignment of the femoral stem, influence the dislocation rate and long-term survival rate. 3D-printed patient-specific instruments (PSI) can assist in acetabular reaming positioning, femoral neck osteotomy, and rotational alignment of the femoral stem. For patients with Crowe type IV developmental dysplasia of the hip (DDH), characterized by an extremely shallow acetabulum, severe shortening and rotational deformity of the proximal femur, and contracture of the surrounding soft tissues, traditional surgery is extremely challenging. Using 3D printing technology to design an integrated acetabular prosthesis (IAP) that matches the size and shape of the acetabular bone defect in DDH enables perfect fit with the defect, ensuring the integrity of the hip joint and restoring its center of rotation. In addition, it reduces micromotion and friction between multiple components, ultimately enhancing the long-term stability of the acetabular prosthesis, making acetabular reconstruction in DDH more reliable and safer [14].

In total knee arthroplasty (TKA), restoration of lower limb mechanical alignment and soft tissue balance are key factors determining long-term outcomes. Traditional surgery relies on intramedullary or extramedullary alignment guides and intraoperative measurements, which are associated with a certain degree of error. 3D-printed patient-specific instruments (PSI) can precisely guide distal femoral osteotomy, tibial plateau osteotomy, and rotational alignment, enabling individualized mechanical axis reconstruction. Customized porous tantalum implants and spacers can promote bone ingrowth, reduce the loosening rate, help restore skeletal integrity and joint stability, and significantly improve function and alleviate pain [15].

3.4. 3D printed orthoses

Traditional manufacturing techniques make custom devices costly and inaccessible to many patients, whereas 3D printing enables the rapid production of personalized prostheses and orthotic devices, significantly reducing costs and improving accessibility. In addition, custom designs can be easily modified and adjusted, enhancing comfort and functionality for patients with limb differences or orthopedic conditions. 3D-printed orthoses offer numerous significant advantages during the treatment process. Three-dimensional scaffolds can effectively reduce swelling and excessive tension in the muscles of the wrist, while improving motor function and the ability to extend the arm [16]. Their nearly perfect fit also reduces friction between the material and the skin. Overall, 3D-printed orthoses surpass traditional alternatives in terms of comfort, pain relief, and convenience in daily use. They provide greater mobility and improved motor function, which is particularly important for patients with limited mobility. One study showed that after four weeks of using a three-dimensional orthosis, pain was significantly reduced compared with the plaster cast and traditional orthosis groups, as assessed by the PRWE and VAS scales [17]. 3D printing has also opened new possibilities for the design and fabrication of prostheses, offering more customized, lightweight, and cost-effective solutions to improve patients' quality of life. However, in certain cases, traditional materials may be more effective, indicating that there is still room for improvement and optimization in orthopedic 3D printing technology.

3.5. Others

3D-printed porous scaffolds (e.g., PCL/HA, PLGA/β-TCP) can mimic trabecular bone structure and be loaded with growth factors such as BMP-2 and VEGF to promote osteogenesis and vascularization [18]. Bioprinting involves loading MSCs and iPSCs into hydrogels to achieve cartilage and bone tissue construction [19]. Incorporating antibiotics (e.g., vancomycin, gentamicin), metal nanoparticles (e.g., Ag, Zn), or chitosan into 3D-printed materials can confer local antimicrobial properties to implants, thereby reducing the risk of periprosthetic infection [20]. 3D-printed anatomical models and surgical simulators can be used for the training of medical students and residents, enhancing anatomical understanding and surgical skills.

The integration of AI with 3D printing is driving transformative innovations in orthopedics, particularly in the fabrication of casts, implants, and prostheses. AI enhances the 3D printing process through real-time continuous monitoring of material properties, layer alignment, and thickness, reducing material usage in line with sustainable practices [21]. AI-driven systems can analyze large volumes of patient data and medical images, enabling the customization of implants based on individual anatomical and biomechanical needs, thereby improving surgical outcomes and reducing complications [22].

4. Conclusion

3D printing technology has transitioned from the laboratory to clinical practice, demonstrating significant value in spinal surgery, trauma orthopedics, joint surgery, orthotics, and medical education. Currently, the next-generation 4D printing technology has emerged, introducing the dimension of time. Leveraging the ability of shape-memory materials to self-deform in vivo, it holds promise for minimally invasive implantation and self-expansion to its predefined configuration, thereby better meeting patient needs. Although challenges remain in areas such as materials, cost, and regulation, with the deepening of multidisciplinary collaboration, advances in materials science, and the integration of AI, 3D printing is expected to become one of the core technologies in orthopedic precision medicine, driving orthopedic treatment toward greater personalization, efficiency, and sustainability.

Disclosure statement

The authors declare no conflict of interest.

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