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Application Progress of 3D Printing in the Field of Spine Surgery

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Abstract: The application of 3D printing technology in the field of biomedicine has made breakthroughs in recent years, and it has achieved clinical three-dimensional manufacturing by breaking through the limitations of two-dimensional images such as computed tomography CT or magnetic resonance imaging (MRI) and has broad prospects in the field of spine surgery. The clinical application of 3D printing in spine surgery mainly involves preoperative planning and surgical simulation, model and implant fabrication, surgical aid guide fabrication and patient education, etc. This article will summarize the application status of 3D printing technology in the field of spine surgery and look forward to its future development.

1. Introduction

3D printing, also known as additive manufacturing, proposed by Hull in 1986, is a kind of digital model data, using viscous materials to fuse layer by layer, stacked into the required three-dimensional parts, the current application of raw materials includes metal or ceramic powders, solid and liquid polymers, bio gels and living cells [1-3]. This technology, breaking through the limitations of two-dimensional images, makes it possible to manufacture physical 3D models from computer-aided design to additive manufacturing. 3D printing technology has been skillfully applied to the medical field, through the use of CT or MRI and other medical imaging technology, to obtain the patient's accurate bones, joints, and other parts of the contour data, accurately produce a three-dimensional model in line with the patient's anatomical morphology, copy or make complex simulation, visualization, high-precision bone structure. 3D printing technology has made extensive attempts in orthopedics through the above characteristics, involving preoperative planning and surgical simulation, model and implant fabrication, surgical aid guide fabrication and patient education, etc. [4-6]. This article reviews the relevant literature at home and abroad and reviews the research progress of 3D printing in spinal surgery.

2. 3D Print

The workflow of 3D printing begins with data acquisition in various scanning technologies; this is followed by data processing using computer-aided design software; finally, the data is transferred to a 3D printing device to stack the desired material layer by layer, additively manufacturing the structure of the entity. In the manufacturing process, this additive manufacturing solution quickly replaced the previous "subtractive manufacturing" method [2, 7].

2.1. Workflow for 3D Printing Technology

First of all: 3D printing Acquisition of raw image data: Obtain raw image data through scanners, CT, MRI images, etc., and output the data obtained in the above way in DICOM format. The second step is to import the medical image data (DICOM file) into the modeling software. Such as Mimics, Amira, Rhino, 3D Slicer, etc. Among them, Mimics is one of the most commonly used software. The modeling software processes the imported image into a spatial model representing the actual tissue anatomy and then models the target part in 3D to obtain an STL file. Finally, the STL file is imported into a computer system and layered into two-dimensional slice data, which is printed layer by layer through a computer-controlled 3D printing system and superimposed into a three-dimensional solid. Then, through subsequent curing and polishing, a rapidly formed 3D-printed solid model is obtained [3, 8, 9].

2.2. Polymer-Based Printing Process

The widely used polymer materials currently used in 3D printing are Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS), and Stereolithography (SLA) to manufacture polymer parts [10] (Figure 1).

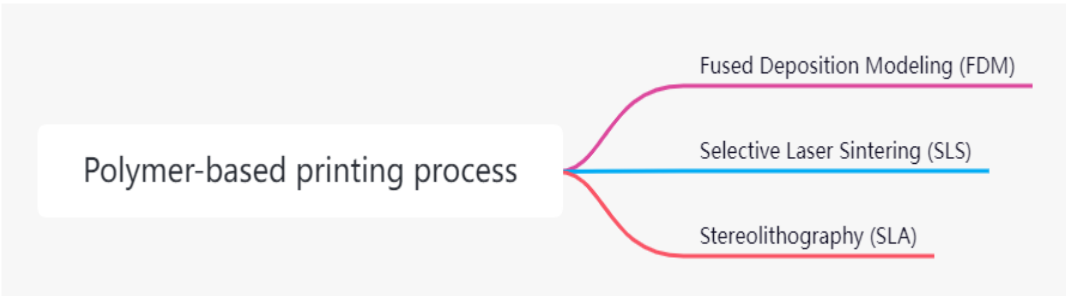

Figure 1. Polymer-based printing process

The technique of layer-by-layer depositing thermoplastic filaments on a build platform is referred to as FDM, sometimes known as fused filament fabrication (FFF) [11-14].FDM's material is a thermoplastic polymer in the form of a filament. The heated polymer filament is placed on the heated platform or print bed after being heated to a semi-solid state. The nozzle follows the path of the final object in the specified layer. When the material is extruded, the nozzle again follows the path of the object in the specified layer. The slicer slices the model layer by layer to generate the path followed by the nozzles and generates G-code (computer numerical control programming language), which the nozzles in each layer follow. The nozzle determines the height of each travel according to the layer thickness of the model. The responsible parameters for the fractional behavior of 3D printed parts are nozzle temperature, bed temperature, and layer thickness. FDM is a contact printing method in which nozzles are used to deposit materials directly layer by layer. Compared with other methods, FDM has the most process simplicity and cost-effectiveness in printing. Because the process simply heats the filament polymer to a semi-solid state and deposits it directly on the printing bed. FDM 3D printers can become the most economical and widely used 3D printers, but the printing time is slightly slower than SLS, many different materials cannot be integrated with the printing process, and the finished product resolution and surface gloss are relatively poor [14] (Figure 2).

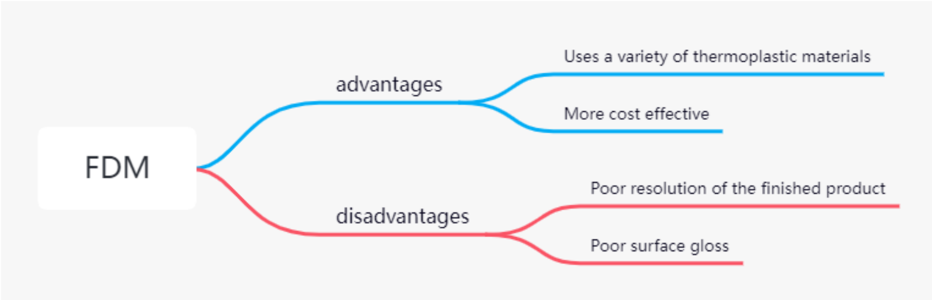

Figure 2. Advantages and disadvantages of FDM

Selective laser sintering (SLS) is widely used in additive manufacturing techniques using a thermoplastic polymer in powder form, a process for producing objects from powder materials, and a variant of powder bed melting [15]. The fabrication process is carried out in a closed chamber using one or more lasers, under the influence of high-power lasers, the powder is melted by molecular diffusion, and the particles are selectively melted layer by layer on the surface. As in FDM, the movement of the laser is again determined by the G-code generated by the slicer. After the sintering process is complete, the parts can be extracted from the platform [16-20]. Compared to FDM, SLS is a relatively complex process that requires the movement of two systems: a roller and a laser light [10]. The raw materials used in SLS vary widely and require complex auxiliary processes for pretreatment. Therefore, SLS 3D printers are more expensive than FDMs. However, the material utilization rate of SLS is significantly higher than other methods, and the un-sintered material can be reused, reducing waste. The process still suffers from the shortage of mechanical properties, and less direct application in the manufacture of functional metal parts(Figure 3).

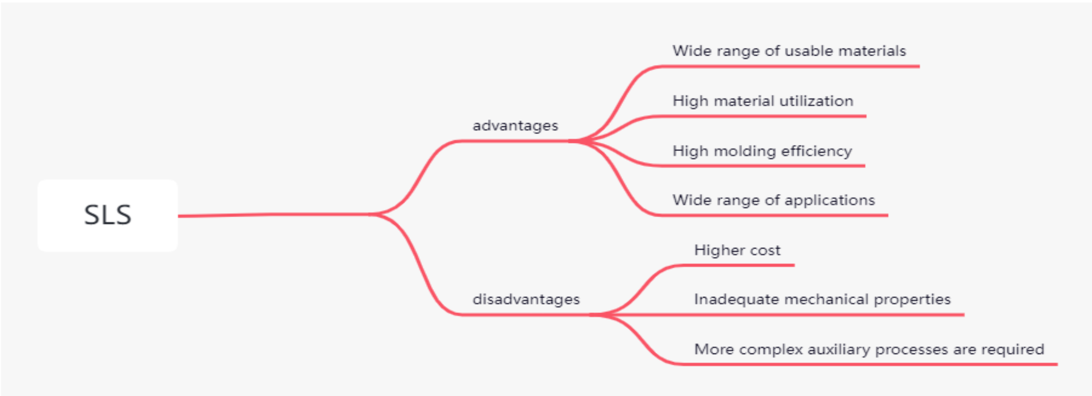

Figure 3. Advantages and disadvantages of SLS

The material used in the Stereolithography apparatus (SLA) is photosensitive thermoset polymers [21], the first developed 3D printing technology that uses photopolymerization for 3D printing and cures the resin by absorbing photopolymerization triggered by light [22]. The principle of the architecture is to reuse the resin cured layer by layer, printing the desired product layer by layer. The energy of the light source and the exposure time determine the thickness of the layer [23]. SLA remains the gold standard in the industry because of its high precision and stable performance to achieve uninterrupted production and high resolution [24-26]. At the same time, SLA 3D printing is being chosen more often because of its fine features, smooth surface finish, ultimate part precision and accuracy, and mechanical attributes like isotropy, water tightness, and material versatility. But the material is relatively expensive compared to other 3D printing methods. Special attention should be paid to the high requirements of SLA for the use of the environment, with toxicity and odor, requiring an airtight environment(Figure 4).

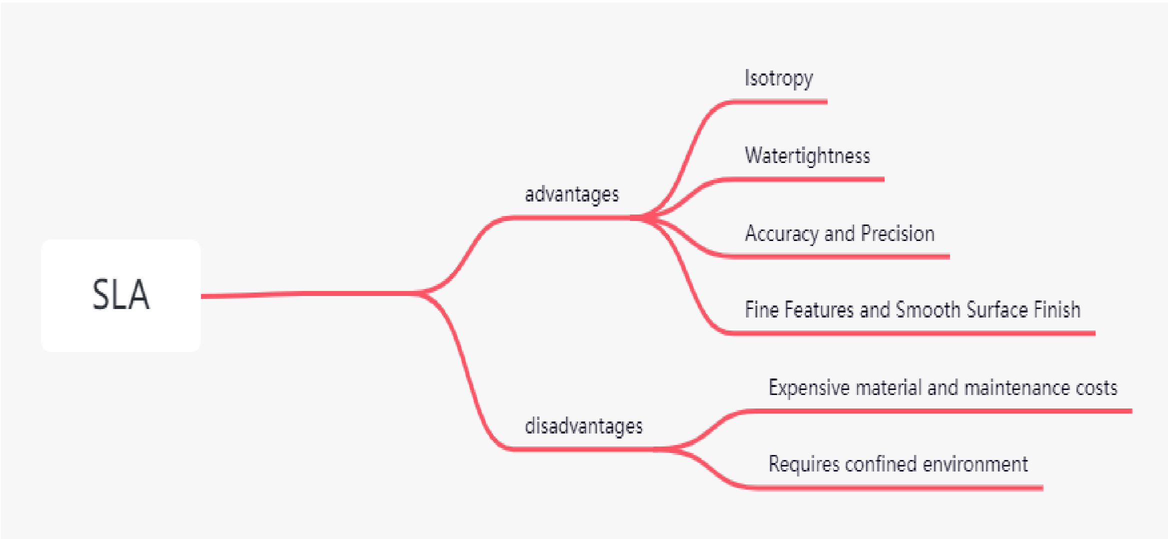

Figure 4. Advantages and disadvantages of SLA

According to a recent study [24], all printing methods can obtain reasonable results in terms of accuracy, and we can choose printing technology based on the simplicity of printing, mechanical properties, printing time, limitations of the printed material, and requirements for layer resolution.

3. Application of 3D Printing in Spine Surgery

Since the discovery of 3D printing and its benefits, custom implants, anatomical models, molds for the production of prosthetics, and surgical guidance have all been widely used [27, 28]. The means of manufacturing 3D printing are increasing from the variety of manufacturing materials to the requirements for accuracy and reliability, and it is now possible to provide patients with personalized devices. 3D printing has been successfully applied in the field of medicine, where orthopedics and neurosurgery are early and eye-catching [28-32]. D'Urso et al. combined the potential of 3DP with spinal surgery in 1999, allowing accurate patient-specific spinal morphology to be printed in physical form [33]. This opens a chapter for the application of 3D printing technology to spinal surgery. 3D printing technology can reproduce complex local anatomical structures and their position relationships in the human body in three-dimensional visualization, which makes complex spinal surgery simple and functional reconstruction more perfect. At present, the application of 3D printing technology in spinal surgery includes printing fracture models for preoperative planning and surgical simulation, printing personalized implants, manufacturing surgical guides or bone repair, and patient education [34, 35].

3.1. Preoperative Planning and Surgical Simulation

Spine surgeons often rely on the visual aids of CT or MRI and their own clinical experience to make their judgments when performing surgical operations in the field of spine surgery, but spinal surgery is designed in a large area, with anatomical complexity, osteologic complexity, and a tightly structured distribution of sensitive neurovascular elements. Traditional two-dimensional images do not fully represent the complex structures and tricky contingencies that doctors face [36]. Yang M et al. [36] created subject-specific spine models that could be used in the preoperative planning process by using 3D printing technology compared to idiopathic scoliosis performed with bare hands without image guidance. The results showed that compared with the conventional group, the 3D printing preoperative planning group had significantly shorter operation time, significantly reduced perioperative blood loss and blood transfusion, and increased postoperative Hb. However, there were no significant differences in morbidity, length of hospital stay, postoperative imaging results, or pedicle screw deviation compared with conventional groups' personalized implants. Jug M. et al. [37] showed a case of a 3D printed model to assist cervical spine instruments, using 3D virtual planning to evaluate and plan retrocervical spine fixation surgical plans, using 3D printed models to confirm the feasibility of fixation "in vitro" before surgery, and minimizing the possibility of intraoperative implant-spine mismatch. The outcome was that the intraoperative conditions were exactly similar to the preoperative plan and the screws were successfully inserted as planned. Postoperatively, the child had a complete neurological recovery with no signs of instrumentation fusion-related pathology and no signs of spinal failure 2 years after surgery. The printed 3D model offers the possibility of better "in vivo" visualization and perception of the spinal anatomy, even in the absence of intraoperative spinal navigation, which facilitates screw placement and reduces the chance of intraoperative complications.

3.2. 3D Printed Implants in Spine Surgery

With the popularity of custom 3D printing technology and the continuous advancement of biological tissue engineering, it is possible to produce complex structures with high precision requirements in a short time due to their unlimited design freedom. Based on this powerful advantage, 3D printing technology can design sophisticated personalized vertebral prostheses based on patient characteristics and complex spinal anatomy. This is necessary for spinal surgery because personalized implants can be tried to provide patients with the most important issues of structural integrity and spinal stability in spinal reconstruction surgery. And, for complex cases, 3D printing of specific implants can bring personalized solutions to rare problems.

Xu et al. [38] reported for the first time a case of primary Ewing sarcoma in the C2 vertebrae of a young patient who successfully restored the stability of his upper cervical spine using a splenectomy and reconstruction using "the first-ever 3D printed vertebrae." The study uses the concept of porous metal scaffolds to 3D print customized self-stabilizing artificial vertebral bodies (SSAVBs) to replace the excised cancerous vertebral bodies, which not only provide mechanical support for the spine, but also facilitate bone growth into the trabecular foramen, and also maintain biomechanical resemblance to normal cancellous bone. After surgery, his neurological function improved, and a year after surgery, sagittal reconstruction images showed evidence of osseointegration of the implant, no sinking or displacement of the structure, and no local recurrence of the tumor. This study not only printed the first-ever artificial vertebrae by utilizing the precision of 3D printing technology manufacturing and the characteristics of personalized new designs but also concluded that porous metals can be used as biochemical candidates for anterior cervical implants in terms of their biochemical stability, biocompatibility, and bone induction capabilities. Yang et al. [39] reported the first case of biomechanical reconstruction in six-layer recurrent chordoma using individualized 3D-printed artificial vertebral bodies. Pain and weakness symptoms were significantly improved postoperatively, and no evidence of recurrence was found at 9 months follow-up. Radiography did not observe settling, displacement, or rupture of the prosthesis. The study argues that 3D printing technology custom-made prostheses could help solve complex internal fixation procedures and simplify surgical procedures. Personalized 3D-printed implants can complete fixed fusion at the spinal transition point of complex structures, showing great development prospects for complex spinal tumor surgeons. Li et al. [40] reported that 1 case of titanium alloy microporous individualized implant was developed by 3D printing technology to conduct bone reconstruction and restore the stability of the atlantovertebral for a rare case of Atlantic solitary plasma cell tumor. There were no related complications after surgery, the patient's pain was significantly reduced and the neurological symptoms were significantly improved. X-rays and CT scans of the cervical spine showed that the implant was achieved in a high way with the preoperative plan. Due to the complex anatomical and osteological complexity of the cervical spine and the tightly structured distribution of sensitive neurovascular elements, higher precision is required during the implantation of plants in the cervical spine. 3D-printed personalized implants designed according to the patient's anatomy as well as surgical and biomechanical requirements offer the possibility of this need for high precision, which is essential for cervical spine surgery.

At present, for the repair of any bone defect, in addition to waiting for the link of bone tissue in the early stage, it is necessary to use the intervention of autologous bone, allogeneic bone, or artificial bone to fill in the later stage to complete the repair of a bone tissue defect, at the same time, autologous bone grafting is known as the gold standard for repairing bone defects. But in recent years, 3D printing microporous implants have broken through the limitations of traditional concepts and brought new methods for bone defect repair. Instead of autologous bone, metal materials are used as fillers for bone defects.

Zhang et al. repaired a 19 cm spinal defect caused by chordoma, a 19 cm personalized Ti6Al4V implant was implanted one month after the spinal lumpectomy and fixed with pedicle screws to repair the T12-L3 defect. The results of the surgery are satisfactory and the bone heals well. Postoperative imaging showed that the porous implant successfully reconstructed and stabilized the bone defect, and imaging images recorded progressive new bone formation within the defect. Histology images show that the proximal interface of bone defect is well integrated with the host bone, tightly interlocked with the titanium pillar, and forms a continuous structure. No loosening, sinking, or implant displacement of the implant-bone complex was observed, nor other mechanical complications. The treatment of large spinal defects in this study showed that 3D-printed porous implants can achieve a strong "implant-bone" fusion. No autologous bone, allogeneic bone, additional growth factors, or bone inducers were used during this treatment, resulting in cost savings and avoidance of complications associated with autologous bone or allogeneic bone.

3.3. Manufacture of Surgical Guides

Studies have shown that surgical guides are well used in orthopedic, maxillofacial, and dental surgery in addition to spine surgery. the initial application of 3D printing technology in spine surgery is the creation of drilling guides for the accurate placement of pedicle screws. The use of surgical guides can shorten the operative time, reduce intraoperative radiation, facilitate access, improve medical outcomes in spine surgery, and allow for outcomes that are progressively independent of the surgeon's experience [27]. In a study of cadaveric specimens, the use of a personalized cervical arch guide for nail placement was found to greatly improve the accuracy of screw placement. This intraoperative method of guiding pedicle screw placement using a 3D guide applies to any segment of the spine.

Liu et al. used a multi-level 3D printed drill bit guide plate to place pedicle screws to correct severe scoliosis. The preoperative design and manufacture of 3D printed multi-level templates based on the anatomy of the most severely deformed segments. Then, by comparing the pedicle screw inserted according to the trajectory of the drilling template with the screw placed by bare hand, the results showed that the accuracy of nail placement was significantly higher than that of the traditional manual nail placement method, and the difference was statistically significant. In addition, the 3D-guided thoracic arch nailing technique also offers great accuracy, safety, and convenience. Sugawara et al. successfully simulated the preoperative simulation by analyzing the preoperative chest CT images using 3D imaging software, printing the patient-specific screw guide template system, and planning the screw insertion trajectory. A postoperative CT scan confirmed that the thoracic pedicle screw was well placed and did not invade the pedicle cortex. It is concluded that 3D printing personalized screw guide template systems for intraoperative navigation can improve the accuracy of nail placement, and reduce surgical time and radiation exposure.

3.4. Patient Education

Preoperative doctor-patient communication has always been regarded as one of the most concerning and unmissable issues in physicians' clinical work [7]. The patient's correct understanding of their disease diagnosis and treatment plan will greatly improve the cooperation and communication efficiency of the doctor. Studies have shown a correlation between quality doctor-patient communication and improved patient outcomes. Patients' misperceptions and insufficient understanding of their diseases are likely to lead to insufficient trust in the physician and delay in making the necessary treatment plan. Studies have shown that more than 16% of patients choose to cancel surgery due to insufficient understanding of the treatment plan. Making 3D-printed fracture models in orthopedic clinical practice can improve the efficiency of communication between patients and surgeons, improve patients' understanding of their injuries, enhance the informed consent process, and reduce the time and cost of surgery by about 15% while reducing the costs associated with medical-legal proceedings. The 3D printed fracture model intervenes in preoperative communication, which represents that we are taking a step towards more personalized medical treatment, where patients can intuitively understand their anatomy, more comply with the surgical plan given by the surgeon, and reduce unnecessary anxiety. This is undoubtedly a great help to our clinical work.

4. Discussion

3D printing technology in spine surgery is currently leading the way in tissue engineering for preoperative planning and surgical simulation, fabrication of models and implants, production of surgical aid guides, and patient education. However, the cost of treatment and the limitations of printing materials, as well as the time lag caused by printing models, also limit the clinical application of 3D printing technology. In the area of spinal stability reconstruction, the use of 3D printing allows for precise refinement of locally unstable structures, restoring the integrity of the damaged structure and effectively improving the appearance and rebuilding stability. However, as an implant, the issue of biohistocompatibility remains to be advanced, which places high demands on the materials used for endosseous implants [34, 35].

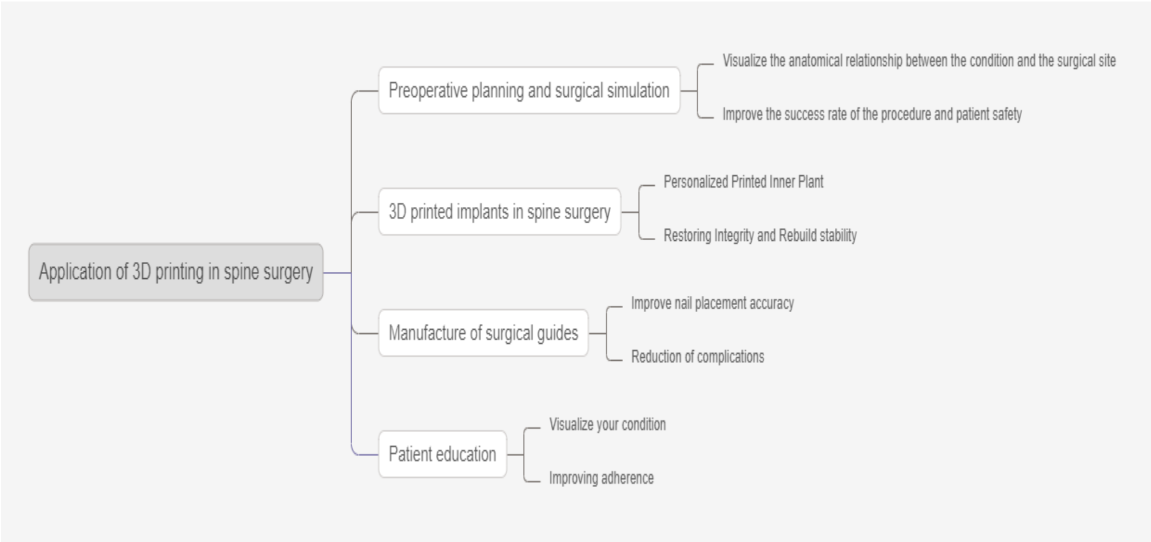

Figure 5. Application of 3D printing in spine surgery

The use of 3D printing technology to print anatomical models during preoperative planning and simulation allows physicians to gain a clear understanding of the condition and the anatomical relationships of the surgical site, thereby improving the success of the procedure and the safety of the patient. The design of 3D printed implants allows for 3D reproduction of complex anatomical structures based on patient specificity and the selection of special materials based on histocompatibility to restore the structural integrity of damaged spinal segments and rebuild spinal stability. In terms of surgical guide fabrication, the use of 3D guides to assist with arch nailing can improve nail placement accuracy and reduce complications. In terms of patient education, 3D printing technology can be used to reproduce three-dimensional anatomical structures so that patients can visualize their conditions and improve their understanding of their diseases, thereby increasing their medical compliance. In addition, 3D-printed anatomical models can also be used for preoperative training. By interacting with 3D-printed customized anatomical models, trainees can acquire basic operational skills, allowing the trainer to gain some initial surgical experience (Figure 5).

Today, the predictable boom in 3D printing technology, materials science, and bioprinting will increase the use of 3D printing in spine surgery as the cost of printing is reduced and the process streamlined, the accuracy of printing is improved, and satisfactory long-term follow-up results are collected.

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Data Availability

The datasets used during the current study are available from the corresponding author on reasonable request.

Conflict of Interest

The author states that this article has no conflict of interest.

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