THREE-DIMENSIONAL PRINTING IN SPINAL SURGERY: UPDATE AND SYSTEMATIC REVIEW

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Review Article

THREE-DIMENSIONAL PRINTING IN SPINAL SURGERY: UPDATE AND SYSTEMATIC REVIEW

IMPRESSÃO 3D EM CIRURGIA DA COLUNA VERTEBRAL: ATUALIZAÇÃO E REVISÃO SISTEMÁTICA

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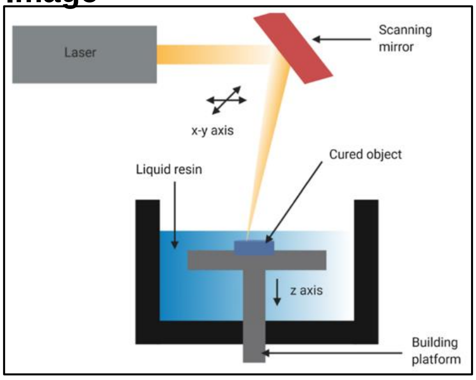
Image



Schematic of stereolithography (SLA) 3D printing

Central Message

Three-dimensional printing is considered the "*third industrial revolution*". It was developed as a promising innovation for many areas, including medicine. There are many ways to use 3D printing in spinal surgery: patient and healthcare professional education, preoperative applications such as surgical planning and intraoperative applications. This systematic review carries out an update on the use of 3DP in spinal surgery.

Perspective

3D printing can now be considered another option for improving the surgical approach to spinal diseases, especially in complex cases with challenging anatomy. Biomodels increase surgeons' ability to perform more precise surgeries, in less time and with greater accuracy.

Author´s contribution

Conceptualization: Francisco Alves de Araújo Júnior
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Writing – review & amp; editing: All authors

ABSTRACT - ***Introduction***: Three-dimensional printing is considered the "*third industrial revolution*". It was developed as a promising innovation for many areas, including medicine. There are many ways to use 3D printing in spinal surgery: patient and healthcare professional education, preoperative applications such as surgical planning and intraoperative applications. ***Objective***: To carry out an update and systematic review on the use of 3DP in spinal surgery. ***Method***: A systematic literature review was conducted using the PubMed database in January 2024, using the terms "*spine surgery*" and "*3D printing*". Articles published between 2014 and 2024 and only clinical trials were selected. Articles that were not in English or Spanish were excluded. This review followed the Preferred Reported Items for Systematic Reviews and Meta-Analysis (PRISMA) guideline. ***Result***: After screening and evaluation, 10 articles were included. Regarding the diseases studied, the majority were deformities (n = 3) and trauma (n = 3), followed by degenerative diseases (n = 2). Two articles dealt with surgical technique. Six studied the creation of personalized guides for inserting screws; 2 were about education, 1 related to educating patients about their disease and the other to teaching residents surgical technique; 2 other articles addressed surgical planning, where biomodels were printed to study anatomy and surgical programming. ***Conclusion***: Three-dimensional printing biomodels and personalized guides for screw implants are useful for use in spinal surgery. The use of this technology has enabled patient and medical team education, as well as optimizing preoperative planning and reducing surgical time and radiation exposure in spinal surgery.
KEYWORDS - Three-dimensional printing. Spine surgery. Technology.

RESUMO - ***Introdução*****:** A impressão tridimensional é considerada a "*terceira revolução industrial*". Foi desenvolvida como inovação promissora para muitas áreas, incluindo a medicina. Há muitas maneiras de usar a impressão 3D em cirurgia da coluna vertebral: educação de pacientes e profissionais de saúde, aplicações pré-operatórias, como planejamento cirúrgico e aplicações intraoperatórias. ***Objetivo***: Realizar atualização e revisão sistemática sobre o uso do 3DP em cirurgia da coluna vertebral. ***Método***: Foi realizada revisão sistemática da literatura na base de dados PubMed em janeiro de 2024, utilizando os termos "*spine surgery*" e "*3D printing*". Foram selecionados artigos publicados entre 2014 e 2024 e apenas como ensaios clínicos. Foram excluídos aqueles que não estivessem em inglês ou espanhol. Esta revisão seguiu a diretriz *Preferred Reported Items for Systematic Reviews and Meta-Analysis* (PRISMA). ***Resultado***: Após triagem e avaliação, foram incluídos 10 artigos.

Em relação às doenças estudadas, a maioria foi de deformidades (n = 3) e traumas (n = 3), seguidas das doenças degenerativas (n = 2). Dois artigos trataram da técnica cirúrgica. Seis estudaram a criação de guias personalizadas para inserção de parafusos; 2 eram sobre educação, 1 relacionado à educação dos pacientes sobre sua doença e outro ao ensino da técnica cirúrgica aos residentes; outros 2 artigos abordaram planejamento cirúrgico, onde foram impressos biomodelos para estudo de anatomia e programação cirúrgica. ***Conclusão***: Biomodelos de impressão tridimensional e guias personalizados para implantes de parafusos são úteis para uso em cirurgia da coluna vertebral. O uso dessa tecnologia possibilitou a educação do paciente e da equipe médica, além de otimizar o planejamento pré-operatório e reduzir o tempo cirúrgico e a exposição à radiação em operações de coluna.
PALAVRAS-CHAVE - Impressão tridimensional. Cirurgia na coluna. Tecnologia**.**

INTRODUCTION

Additive manufacturing or three-dimensional printing (3DP) is considered by many to be the "*third industrial revolution*". It was developed as a promising innovation for many areas, including medicine.[1,2]

The first research into 3DP dates back to the late 1970s, when various computer-aided additive manufacturing techniques emerged, using different platforms.[2,3] But it was in 1984, the physics engineer Charles Hull invented and patented the first device with the stereolithography (SLA) technique.[4]

Three-dimensional printing has been widely used, from the automotive and aerospace industries to the biomedical and pharmaceutical industries.[2] From the 2000s onwards, it began to be applied more frequently in medicine, mainly in the field of orthopedics, oral and maxillofacial surgery, neurosurgery and spinal surgery, as an innovative modality in the training and planning of surgical procedures.[5,6]

There are many ways to use 3D printing in spinal surgery. Patient and healthcare professional education, preoperative applications such as surgical planning and intraoperative applications such as patient-specific guides and implants are just some of its implications in this field of medicine.[2,5,7]

The aim of this article was to carry out an update and systematic review on the use of 3DP in spinal surgery.

METHODS

A systematic literature review was conducted using the PubMed database in March 2024, using the terms "*spine surgery*" and "*3D printing*". Articles published between 2014 and 2024 and only clinical trials were selected. The ones that were not in English or Spanish were excluded. This review followed the Preferred Reported Items for Systematic Reviews and Meta-Analysis (PRISMA) guideline (Figure 1).

The selected articles were classified into categories based on the use of 3D printing (customized guides, surgical planning and education) and the disease that was addressed (deformity, degenerative, trauma) or study/improvement of surgical technique.

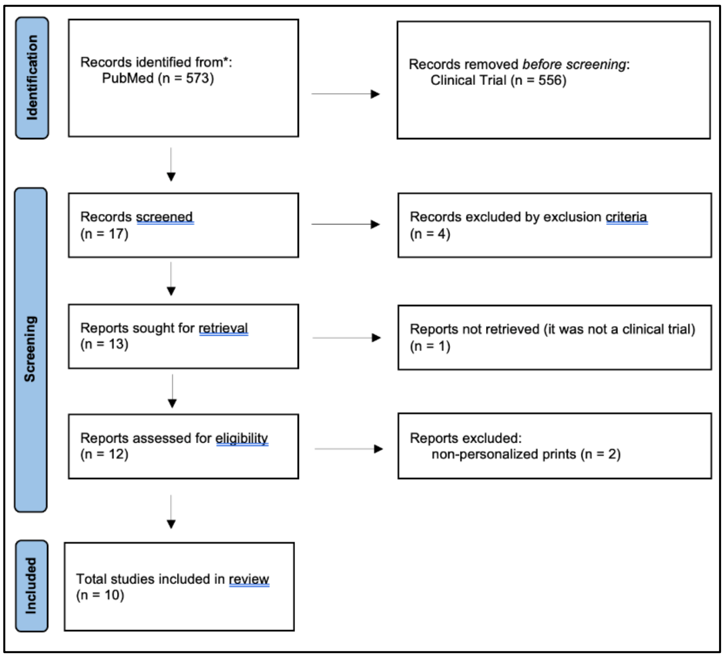


FIGURE 1 – PRISMA flowchart demonstrating the selection of articles

RESULTS

After screening and evaluation, 10 articles were included and are listed in Table 1. Six studied the creation of personalized guides for inserting screws; 2 were about education, 1 related to educating patients about their disease, and the other to teaching residents surgical technique; 2 other articles addressed surgical planning, where biomodels were printed to study anatomy and surgical programming.

Regarding the diseases studied, the majority were deformities (n = 3) and trauma (n = 3), followed by degenerative diseases (n = 2). Two articles dealt with surgical technique.

TABLE 1 – Articles used in the review

AUTHOR (YEAR)	USE / DISEASE	GROUPS / RESULTS
Cecchinato et al. (2019) [8]	Custom guides deformity	Group A: 297 pedicle screws with custom guides. Group B: 243 free-hand pedicle screws. Screws in a safe area were higher in group A (96.1% x 82.9%). Lower radiation dose in group A.
Luo et al. (2019) [9]	Custom guides deformity	PG Group (n = 15): patients operated with custom guides. Control group (n = 17): patients operated using the free-hand technique. Shorter surgical time and better screw location in the PG group.
Zhuang et al. (2019) [10]	Education degenerative	CT/MR group (n = 15): patients received guidance about their disease with the help of CT and MR. 3D reconstruction group (n = 15): patients received guidance about their disease with the help of 3D reconstruction. Personalized biomodel group (n = 15): patients received guidance about their disease with personalized biomodels. Patients in the biomodel group had better understanding and were more satisfied with the explanation about their disease.
Feng et al. (2020) [11]	Custom guides	Group A: 36 side mass screws with custom guides. Group B: 36 free-hand lateral mass screws.

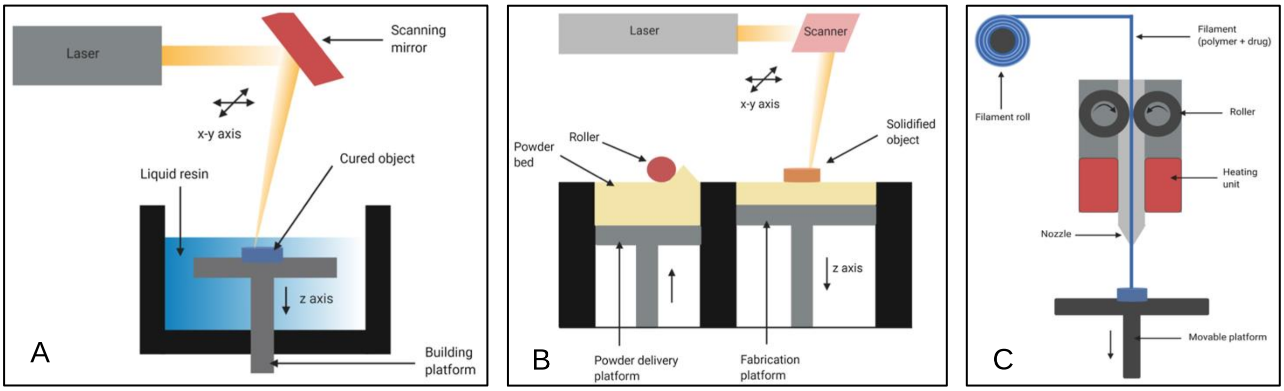
	degenerative	Screws in an acceptable area were higher in group A (88.9% x 61.1%). Screws in excellent area were higher in group A (83.3% x 47.2%). No difference in surgical time and blood loss.
Zhang et al. (2020) [12]	Custom guides trauma	Group A (n = 20): patients operated just with radioscopy. Group B (n = 20): patients operated with personalized guides. Greater accuracy of pedicle screw location in group B. Shorter surgical time, less blood loss and shorter radioscopy time in group B. No difference in pain and postoperative recovery.
Kon et al. (2021) [13]	Education surgical technique	Group L (n = 6) residents learned the procedure technique electronically. Group P (n = 6) residents learned the technique electronically and with a biomodel. Less amount of radioscopy imaging and shorter surgical time in group P.
Ozturk et al. (2022) [14]	Surgical planning trauma	Control group: 16 patients (n = 162 pedicles). Biomodel group: 16 patients (n = 160 pedicles). Shorter surgical time, less blood loss and shorter radioscopy time in the biomodel group. Pedicle screws were more medialized to the spinal canal in the control group.
Pijpker et al. (2022) [15]	Custom guides surgical technique	Group 1 – drill guides (n = 43). Group 2 – drill guides + cannulated screws (n = 22). Group 3 – modular guide for drill and screw (n = 21). Modular guides can improve the accuracy of particularly lumbar pedicle screws. Placement of cervical pedicle screws using 3D printed drill guides appears to be accurate without additional screw guidance.
Zhang et al. (2022) [16]	Custom guides trauma	Group A (n = 20): patients operated with radioscopy. Group B (n = 20): patients operated with personalized guides with a flat end. Group C (n = 20): patients operated with personalized guides with a pointed end. Greater precision in the location of pedicle screws in group C. Shorter surgical time and shorter radioscopy time in group C. No difference in pain and postoperative recovery.
Pan et al. (2023) [17]	Surgical planning deformity	Control group (n = 35): patients operated using the free-hand technique. Group 3DP (n = 35): patients operated with the aid of the patient's biomodel. Shorter surgical time and less blood loss in the 3DP group. Better accuracy in screw positioning in the 3DP group. The rate of complications related to poor screw positioning was higher in the control group.

DISCUSSION

Additive manufacturing principles

Additive manufacturing is a manufacturing process that involves the successive addition of material in the form of layers. The basic principle of this technology is to build sequential two-dimensional slices, similar to the cuts in images generated by computerized tomography (CT) or magnetic resonance imaging (MRI). Each slice is printed one on top of the other, building a three-dimensional prototype. Not only the external details, but also the internal contour is transferred to the prototype, making it possible to make complex anatomical models with all their details.[8]

Although there are several 3D printing techniques, 3 of them are most popular in medical applications (Figure 2). Stereolithography (SLA) involves a photocurable resin that is cured before successive layers are added by means of photopolymerization to create a final prototype. Selective laser sintering (SLS) uses an electron beam or a laser-focused energy source to sinter a bed of fine powder; the powder can consist of nylon, stainless steel and titanium alloys, which can make it suitable for implantation in patients. Finally, fused deposition modeling (FDM) involves a layer of polymer heated with a computer-controlled extrusion nozzle. Although FDM is more cost-effective and easier to use, SLA and SLS are more commonly used in medical applications due to the material's ability to withstand sterilization without damaging the models. The low melting point of FDM material makes its use in a surgical environment more challenging.[9]



Source: Vaz VM, Kumar L. 3D Printing as a Promising Tool in Personalized Medicine. AAPSPharmSciTech. 2021;22(1). Doi: 10.1208/s12249-020-01905-8

FIGURE 2 – Schematic of the three most popular 3D printing techniques in medical applications: A) stereolithography (SLA); B) selective laser sintering (SLS); C) fused deposition modeling (FDM).

Many materials are used in these different 3D printing techniques; for example, thermoplastics such as poly lactic acid (PLA) are commonly used for the fusible filament manufacturing technique, while titanium alloys and chromium-cobalt alloys are used for the laser technique. Researchers can choose different materials according to the 3D printing technique to be used and the properties, cost and color of the materials they prefer.[10]

The steps involved in making a 3D object are: a) preparing the 3D geometric model from two-dimensional images or slices of the object to be printed, using scanners or non-invasive imaging technologies such as CT or MRI; b) obtaining the 3D geometric model in a specific file format for additive manufacturing (for example: STL - *StereoLithography*); c) planning the manufacturing process (choosing the material, slicing thickness, defining the part's support structures); d) manufacturing the part by the 3D printer; e) post-processing, which involves cleaning, finishing and removing the supports. The printing process is fully automated, with no operator intervention. The operator only acts during the planning of the object to be printed.[11]

One of the great advantages of 3D printing is the manufacture of geometrically complex parts with little material waste. The biggest obstacle to applying this technology in developing or underdeveloped countries is still the cost involved in producing the parts, which is directly related to the type of raw material and the printer model.[11]

3D printing in medicine and spinal surgery

3D printing has a wide range of applications in healthcare. The first recorded work in this area dates to the 1990s when neurosurgeon Paul Steven D'Urso developed a biomodel for cranioplasty.[12] Since then, the use of additive manufacturing not only in medicine, but in health in general, has taken on great proportions. One of the reasons for this was the great advance in medical imaging technologies with the improvement of CT and MRI scanners.

Every year, 3DP offers more and more applications in healthcare, helping to save and improve lives in ways never imagined before. It has been applied in a wide variety of healthcare settings, including cardiothoracic surgery, cardiology, gastroenterology, neurosurgery, oral and maxillofacial surgery, ophthalmology, otorhinolaryngology, orthopedic surgery, plastic surgery, pulmonology, radiation oncology, transplant surgery, urology and vascular surgery. The 3 main pillars of this new technology in medicine are the ability to treat more people where it wasn't possible before, minimize the risks of surgical complications and optimize the length of surgical time. In this way, 3D printing has the potential to significantly improve the level of understanding of the disease involved and its anatomical changes, especially in complex cases.[1,13]

There are many ways in which 3D printing can be used in the field of spinal surgery. It can be used to educate patients about their illness and proposed treatment, to teach and improve healthcare professionals, especially during medical residency, to study complex cases of spinal deformity and for surgical planning.[14-16]

The first biomodelling of the spine was developed in 1999 by Paul D'Urso et al.[17] to study five complex cases of spinal deformity. The authors concluded that 3D printing enabled more assertive surgical planning, familiarity with the spinal anatomy of the cases and facilitated communication and patient education about the disease and proposed treatment.[17] Subsequently, other authors were able to apply biomodels for surgical planning and patient education.[5,18]

Medical and patient education

Biomodels have already been applied for surgical planning and resident education in cases of complex spinal fractures. They not only provide trainees with the opportunity to practice their surgical skills before entering the operating theatre, but also help in choosing the right size of screws with the appropriate angle of approach at the time of operation during implantation. The 3D model can make the placement of pedicle screws by the freehand technique in cases of severe spinal cord trauma safer and with acceptable precision, thus reducing operating time, estimating blood loss and reducing intraoperative fluoroscopy during surgery.[19] Other authors have developed a biomodelling of the lumbar spine to train residents in percutaneous procedures for pain intervention (foraminal block, dorsal root middle branch block and lumbar sympathetic chain block). To simulate a patient's torso, a layer of foam was placed over the spine and covered with silicone. Training using this simulator reduced the procedure time and the number of images obtained by radioscopy.[20]

One of the great uses of 3D printing is in educating patients about their disease.[2,21] Zhuang et al.[22] randomized 45 patients with lumbar degenerative diseases into 3 groups: a) an educational programme presented by CT and MRI images; b) 3D reconstructions; or c) personalized 3DP models and assessed the degree of patient education. The authors concluded that the level of understanding and satisfaction was better when using the personalized 3D models.[22]

Personalized guides

The development of 3D-printed guides for implanting pedicle screws has been studied in recent years with the aim of improving surgical technique, preventing complications, reducing surgical time and trans-operative radiation.[9,23-27] The use of pedicle screw guides was first reported in 2005 in a cadaveric study by Berry et al.[28] in which customized guides printed in four different designs were used in cadaveric specimens with varying degrees of success.

Since then, research has shown the benefit of customized guides in spinal screw implants. A cadaveric study showed a lower rate of malposition of cervical pedicle screws when inserted using guides compared to those inserted without the aid of customized guides.[25] Lu et al.[29] developed guides for inserting cervical pedicle screws and proved that the method significantly reduces the duration of the operation and radiation exposure for members of the surgical team. Feng et al.[30], in a randomized study with 6 patients, evaluated the positioning of lateral mass screws implanted with the aid of guides printed by additive manufacturing and concluded that these screws were better positioned than those implanted without the guides. Sugawara et al.[31] also successfully 3DP guides for C1 and C2 screw implants. There is also applicability of customized guides for percutaneous thoracolumbar screw implantation and minimally invasive procedures.[32-34]

Zhang et al.[29] studied 2 types of customized guides for inserting percutaneous pedicle screws, 1 with a shallow end and the other pointed, and concluded that these allowed for better accuracy in positioning the screws. Other authors compared the positioning of pedicle screws placed with the aid of a drill guide vs. a guide that made it possible to insert the screws from the inside, which they called a modular guide.[25] This study was conducted on cadavers and concludes that modular guides can improve screw insertion; however, at the cervical levels, 3DP drill guides have already demonstrated very high accuracy and therefore there is no benefit from additional screw guidance techniques.[25]

Complex cases and spinal deformity surgery

Surgery to treat spinal deformities such as scoliosis and kyphosis is always challenging due to the distortion of the anatomy, especially in congenital cases. 3DP has been used in these cases, both for more assertive preoperative planning and for making personalized guides for inserting pedicle screws.[9,23,24,26,27] Izatt et al.[18] studied 26 patients with complex spinal diseases (tumours and deformities) and used biomodels for surgical planning and concluded that the identification of anatomical details was better than in imaging tests in 65% of cases and that in 11% of patients anatomical details were identified only in biomodels.

Checchinato et al.[23] carried out a randomized study placing patients with spinal deformity in a group where pedicle screws were implanted using customized guides printed by additive manufacturing (group A) and another where the screws were implanted *free-hand* (group B). The authors observed that 96% of the screws implanted with the aid of the guide were in a safe area, compared to 82.9% in group B. In addition, there was a lower radiation dose during surgery for patients in group A. Luo et al.[24] studied cases of congenital scoliosis and divided the patients into a control group (n = 17), where the pedicle screws were inserted using the *free-hand* technique, and a pedicle guide group (n = 15). The positioning of the screws was analyzed using post-operative CT. The authors concluded that the use of guides printed in additive manufacturing allows for greater accuracy in the positioning of pedicle screws and shorter surgery times and suggest that 3D printing of customized guides could be useful in cases where intraoperative CT scans or navigation are not available.

Pan et al.[26] carried out a study involving patients with scoliosis and 35 patients were placed in a control group where the screws were implanted *free-hand* and another 35 in a group where the surgery was planned with 3D printing of each patient's spine. In this group, they studied the screw entry points and osteotomy sites prior to surgery. The authors concluded that the biomodelling was essential for better positioning of the screws and helped in a more effective osteotomy involving the three columns.

Teixeira et al.[27] made personalized guides using 3D printing techniques to help implant pedicle screws in surgeries to correct vertebral deformities. Four patients were treated, totaling 85 pedicles, and the authors concluded that the prototypes allowed safe preparation of the pedicle hole, with greater precision, and less intraoperative exposure to radiation.

A meta-analysis by Katiyar et al.[9] showed a significant improvement in the accuracy of pedicle screw placement using customized guides with additive manufacturing. This same review showed that the studies that used 3D models of the spine in preoperative planning found it useful and observed an increase in the accuracy rate of screw placement of 89.9%.

Therefore, 3D printing can now be considered another option for improving the surgical approach to spinal diseases, especially in complex cases with challenging anatomy. Biomodels increase surgeons' ability to perform more precise surgeries, in less time and with greater accuracy.

CONCLUSIONS

Three-dimensional printing biomodels and personalized guides for screw implants are useful for use in spinal surgery. The use of this technology has enabled patient and medical team education, as well as optimizing preoperative planning and reducing surgical time and radiation exposure in spinal surgery.

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