

COSTS AND USES OF 3D PRINTING IN SPINAL SURGERY: A SYSTEMATIC REVIEW

*CUSTOS E USOS DA IMPRESSÃO 3D NA CIRURGIA DA COLUNA VERTEBRAL:
UMA REVISÃO SISTEMÁTICA*

*COSTOS Y USOS DE LA IMPRESIÓN 3D EN LA CIRUGÍA DE COLUMNA VERTEBRAL:
UNA REVISIÓN SISTEMÁTICA*

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ABSTRACT

Three-dimensional (3D) printing has rapidly advanced in the healthcare field over the past decades, becoming more accessible due to the wide variety of technologies and materials available. This has secured 3D printing a prominent place in medical specialties, such as spinal surgery, due to its ability to create complex objects, including anatomical models of the spine and its adjacent structures, based on medical imaging. In this specialty, the technology can be used for both preoperative planning and intraoperative support through biomodels and surgical guides. To recognize and explore the use of 3D printing in spinal surgeries, a systematic review was conducted in two databases, focusing on its applications and cost reports. Of the 142 studies identified, only 13 were included in the review due to their strict relevance to the topic. Although scientific studies on the impact of 3D printing in healthcare remain scarce, largely due to a lack of broad, robust research, it was possible to detail the financial impact in the surgical field throughout the entire process of producing 3D-printed objects, from planning and printing to the surgical center. Economic and decision analyses were also conducted. **Level of evidence II; review article.**

Keywords: Printing, Three-Dimensional; Orthopedics; Costs and Cost Analysis; Surgery; Spine.

RESUMO

A impressão tridimensional (3D) se desenvolveu e cresceu de forma rápida na área de saúde nas últimas décadas, tornando uma grande variedade de tecnologias e materiais mais acessíveis. Isto fez com que a Impressão 3D garantisse um espaço cativo dentro das especialidades médicas, como a cirurgia de coluna, em decorrência da sua capacidade de construir objetos complexos como modelos anatômicos da coluna vertebral e estruturas adjacentes a partir de imagens médicas. Nesta especialidade, a tecnologia em questão pode ser utilizada para o planejamento pré-operatório, bem como para o apoio intraoperatório, por meio de biomodelos e guias cirúrgicos. Para reconhecer e explorar a utilização da impressão 3D em cirurgias de coluna, foi realizada uma revisão sistemática em duas bases de dados, com foco em sua utilização e no relato dos custos empregados em seu uso. Dos 142 trabalhos encontrados, apenas 13 foram incluídos na revisão por estarem estritamente relacionados ao tema. Apesar de trabalhos científicos acerca do impacto da impressora 3D na área de saúde ainda ser escasso, principalmente pela falta de estudos amplos e robustos, foi possível detalhar o impacto financeiro no meio cirúrgico durante o processo de produção de objetos impressos em 3D, desde o planejamento, passando pela impressão até o centro cirúrgico. **Nível de evidência II; artigo de revisão.**

Descritores: Impressão tridimensional; Ortopedia; Custos e Análise de Custo; Cirurgia; Coluna Vertebral.

RESUMEN

La impresión tridimensional (3D) se ha desarrollado y crecido rápidamente en la atención médica en las últimas décadas y debido a su variedad de tecnologías, materiales y accesibilidad, lo que hizo que la impresión 3D asegurara un nicho dentro de especialidades médicas como la cirugía de columna vertebral como resultado de su capacidad para construir objetos complejos como modelos anatómicos de la columna vertebral que permean sus estructuras adyacentes a partir de imágenes médicas. En esta especialidad, la tecnología en cuestión puede utilizarse para la planificación preoperatoria y el apoyo intraoperatorio mediante biomodelos y guías quirúrgicas. Para reconocer y explorar el uso de la impresión 3D en cirugías de columna, se realizó una revisión sistemática en 2 bases de datos que se centraron en su uso y el informe de los costos empleados en su uso. De los 142 trabajos encontrados, solo 13 fueron incluidos en la revisión por estar estrictamente relacionados con el tema. Aunque los artículos científicos sobre el impacto de la impresora en el área de la salud aún son escasos, principalmente porque presentan pocos estudios extensos y robustos, fue posible detallar el impacto financiero en el entorno quirúrgico de todo el proceso de producción de objetos impresos en 3D, desde la planificación hasta la impresión y el quirófano. **Nivel de evidencia II; artículo de revisión.**

Descriptores: Impresión Tridimensional; Ortopedia; Costos y Análisis de Costo; Cirugía; Columna Vertebral.

Study conducted by the Instituto Federal de Santa Catarina (IFSC), Florianópolis, SC, Brazil.

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INTRODUCTION

The advent of 3D printing technology, also known as rapid prototyping (RP) or additive manufacturing (AM), has revolutionized several fields of knowledge. Initially adopted in engineering, it rapidly expanded into healthcare. In recent years, it has gained momentum due to its adaptability to a variety of techniques and materials that can be used to print complex objects, which are created and rendered from CAD software and STL files.¹⁻⁴

As 3D printers and associated software become increasingly accessible commercially, demand for this technology is expected to grow in the coming years, with estimates projecting it to reach 35.36 billion dollars by 2028. This is reflected in the widespread use of three-dimensional printing across healthcare professions, ranging from the production of dental models and hearing aids to the construction of models for drug testing, prosthetics, and medical education.^{2,5}

Scientific publications show a sharp increase in research and clinical applications of 3D printing technology in healthcare, with the earliest records dating back to the 1990s. This resource continues to drive progress in orthopedics, particularly in spinal surgery (SS). This is largely due to its ability to reproduce the inherent complexity of the spine (S), which is permeated by fragile structures, especially when these anatomies are affected by various pathologies.¹⁻⁴

Furthermore, 3D-printed products are also used to optimize preoperative planning through surgical guides, designed to assist in positioning for drilling or cutting, thereby ensuring greater accuracy and precision in the technique employed.⁶

Given the early stage of 3D printing's diffusion and the medical community's encouragement of its use, the costs involved in its production and surgical use are highly relevant. In some cases, practice has shown that it is even possible to reduce one or more surgical times. The gains from using 3D models have the potential to offset production costs and further increase the medical institution's profit margin. This is because, in addition to the safety gains for the surgeon, the patient benefits from a more assertive surgery, with shorter duration and, consequently, less use of supplies, human, and physical resources.

The objective of this study is to survey the costs associated with the use of 3D printing in SS through a systematic review of the literature. As a secondary focus to costs, information on the relevance and advantages of 3D printing in SS will be addressed in the discussion. The approach used for the systematic literature review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines.⁷

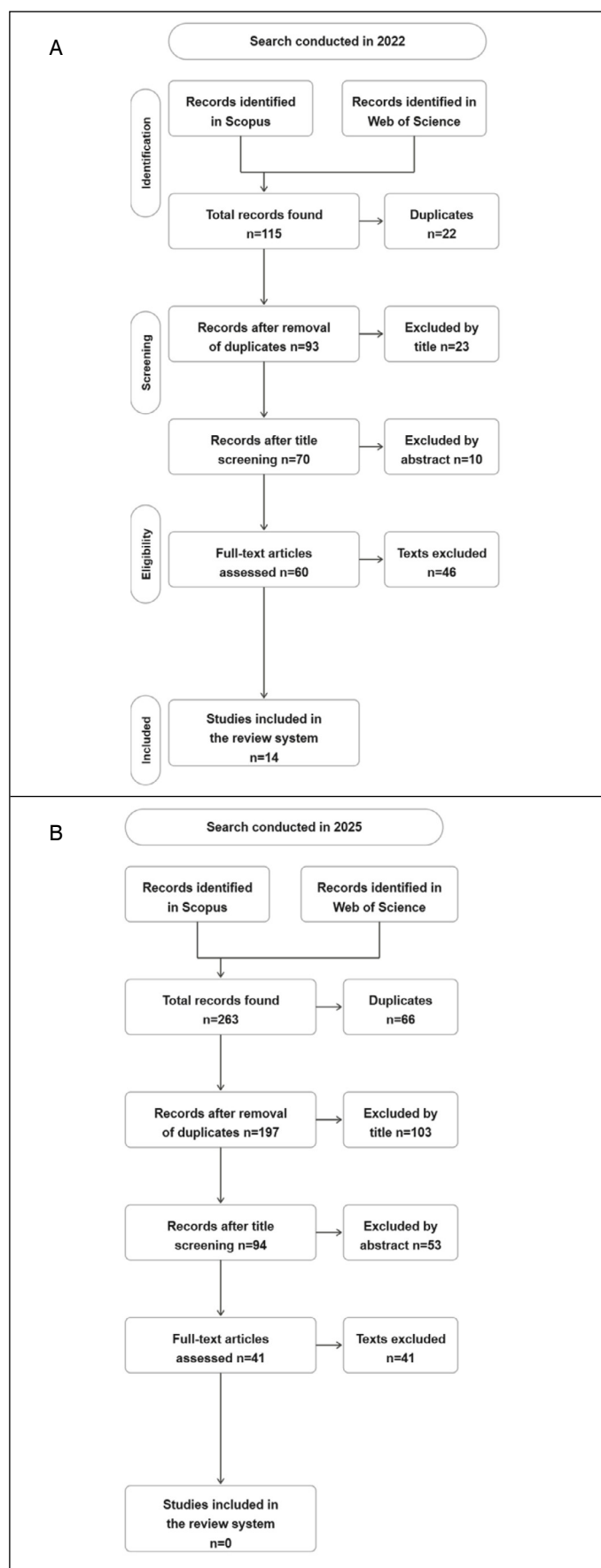
METHODS

The article search strategy was conducted across two databases, *Scopus* and *Web of Science*. Keywords were combined to form the following search syntax in titles, abstracts, and keywords: "(3D print* OR three dimensional AND print AND spine surgery AND cost AND NOT veterinarian*)". The criteria adopted for article exclusion were as follows: studies that did not report costs, animal studies, a non-surgical focus on the spine, a purpose related to image manipulation, a focus on nanotechnology, publication in any language other than English or Portuguese, and publication prior to 2015.

RESULTS

This study was conducted in two stages. The first database search was carried out in October 2022 and yielded 115 articles, of which 22 were duplicates and were removed. After screening articles by title and/or abstract, 61 studies were selected for full-text review, of which only 14 articles were included in this review, as shown in the flowchart in Figure 1A.

A new search conducted in June 2025 using the same databases identified 263 articles on 3D printing in spinal surgery, of which 41 were selected for in-depth analysis. Although new studies on the technology's applications were identified, it was not possible to find updated data on the costs of 3D printing in this specific context; therefore, the articles were discarded, as shown in Figure 1.



Source: research data.

Figure 1. Flowchart detailing the search conducted using the PRISMA methodology.

DISCUSSION

3D printing is in constant expansion due to its continuous evolution, which enables the faster and cheaper development of parts, both simple and of complex topography, whether customized or mass-produced, for various purposes.¹

The aforementioned factors contributed significantly to the adoption of 3D printing in healthcare, with the technology gaining ground in various surgical specialties, particularly orthopedic spinal surgery. The anatomical complexity of this region justifies such prominence, as the technology enables the creation of precise three-dimensional models, facilitating preoperative visualization and minimizing the risk of injury to patients' nerves and vessels.^{2,8}

3D printing enables a highly personalized approach in orthopedics, with applications ranging from customizing surgical cutting and drilling guides to creating implants. This personalization is especially important in cases of severe deformities, such as those of the spine, where each patient's anatomy may vary significantly. Thus, through 3D printing, more precise surgical planning can be achieved, supporting both pre- and intraoperative care. Furthermore, its use contributes to better physician–patient communication by addressing doubts and uncertainties and reducing patient anxiety.²⁻⁷

Surgical Planning

3D-printed biomodels are consistently used in SS due to their ability to accurately replicate spinal structures at life size, with density and stiffness similar to bone, serving as an important tactile 3D reference. The anatomy adjacent to the bone structure can also be selected and printed in different colors or materials to provide a better stereoscopic understanding of the anatomical and pathological complexity. This is because the printed model conveys the complexity of the structures involved in pathologies and their anatomical alterations in a more tangible manner.^{2,9}

Traditional 3D images, although valuable diagnostic tools, have limitations that can compromise the quality of surgical planning. Biomodels, in turn, overcome the limitations of traditional 3D images, offering more precise visualization of anatomical structures and enabling the surgical team to choose the optimal approach for each patient.^{2,9,10}

Pacione et al.⁹ demonstrated this barrier-breaking effect by reporting that their team changed the surgical approach for a cranio-cervical region procedure after analyzing the printed biomodel, as the traditional 3D image limited a clear view of the planes of the area of interest. After analyzing the biomodel, it became clear that a different approach was needed, enabling more detailed planning and simulation of the procedure and influencing instrumentation decisions.^{2,10}

The possibility of early and assertive selection of surgical instruments, such as rods and screws, significantly reduces material waste, operative time, and operational costs, including those of the operating room and surgical team. Furthermore, it reduces blood loss and the perioperative burden on the patient.^{1,2,8-10}

Another benefit of using biomodels is the ability to educate patients more effectively. In this way, it is possible to offer them a clearer, more tangible understanding of the surgical procedure to be performed, significantly reducing anxiety caused by uncertainty. Furthermore, these models are highly valuable tools for training new medical professionals, enabling procedural simulation and refining surgical skills.

The articles report numerous benefits associated with biomodels, but it is still necessary to understand the impact of the biomodel's cost on the final financial cost of the entire process.^{1,2,8-10}

In the literature, few articles reporting costs related to biomodels were found. The articles by Cai et al.¹ and Lopez et al.⁸ cited a study with 126 patients divided into 2 groups: group A using the 3D-printed biomodel and group B using the traditional technique. They found that for the first group, operative time was reduced (212 min vs 184 min), perioperative blood loss was lower (1029 ml vs 846 ml), postoperative hemoglobin loss was smaller (118 g/L vs 115 g/L),

a lower volume of blood transfusion was required (985 ml vs 827 ml), the rate of operative complications decreased (14.5% vs 8%), but hospitalization expenses were slightly higher (US\$ 22,797 vs US\$ 22,143).

Pacione et al.⁹ report a study aimed at producing a resin biomodel for the surgical planning of a complex deformity of the skull base and craniovertebral junction. The model was used as an intraoperative reference, allowing direct comparison to confirm spinal alignment and the reduction of the C1–C2 complex at the foramen magnum. Postoperatively, a new image was obtained, and a new biomodel was printed. The cost was US\$270, and printing took approximately 13 hours.

Goel et al.¹⁰ used 3D printing in the surgical planning of complex craniovertebral anomalies in 11 patients. The models took approximately 5 hours to print, and each cost approximately US\$350. The author notes that the model was of great importance in guiding the surgeon, contributing to reduced operative time and assisting in the precise selection of screw and plate/rod sizes, as preoperative measurements, including the insertion angle, were available, and the pre-selected instruments matched what was needed during surgery.¹⁰

Cost reports for producing surgical planning models vary widely depending on the technology used and the publication date. In the studies reviewed by Lopez et al.⁸, the average cost of printing biomodels is US\$175. 3D printing technology in the treatment of complex spine pathologies proved to be a great ally in reducing operative time. However, the review found no significant difference in intraoperative blood loss between the use and non-use of 3D printing, considering both printed biomodels and printed screw guides.⁸

Tong et al.² produced two models using Fused Deposition Modeling (FDM) technology to investigate the 3D printing process. The first, at 1:1 scale, represented a thoracic spinal scoliosis; printing took 3 days, 8 hours, and 14 minutes, and the material cost was US\$37. The second model, representing a spine with an L1 vertebral body fracture, was produced at half the original dimensions and took 1 day, 8 hours, and 37 minutes to print; the material cost was US\$29. The author reports that both could be used for pre-surgical planning, medical education, or resident training; however, the reduced-scale model may create limitations in planning.²

A study to establish geometric quality criteria for anatomical models was conducted by Eltes et al.³ to select the most widely available printing technologies best suited to a clinical environment. For the study, a computed tomography (CT) image of the L4 lumbar vertebra was selected, processed, and printed using two different technologies: Fused Deposition Modeling (FDM) and Digital Light Processing (DLP).

In the clinical implementation, geometric accuracy was considered when printing a model of the T11–L3 vertebrae of a 12-year-old patient with congenital scoliosis due to an L1 hemivertebra. FDM printing time was 660 min with a total cost of €336, while DLP technology had a printing time of 353 min and a total cost of €605.³

The FDM printer, even without achieving the same precision as DLP, when used for spinal biomodels, did not show a real loss in quality for pre-surgical planning. Thus, by adopting less costly technologies, the healthcare system will benefit from their widespread use.³

Implants

The development of prostheses, scaffolds, and implants to assist in treating degenerative, traumatic, tumoral, and infectious conditions of the spine is also facilitated by 3D printing. Koper et al.¹¹ financially quantified 1 minute of operating room time as equivalent to €16 at the University Medical Center of Maastricht and found that manufacturing implants by 3D printing costs on average between €200 and €250; its use translates into a saving of 25.2 minutes per operation (€403), meaning it is possible to save more than €150 in hospital resources. The estimated values of implants depend on the complexity and the technology used for their fabrication.^{5,11}

Guides

Customized 3D-printed drilling and osteotomy guides are designed to provide professionals with greater precision in screw placement for children and adults with complex anatomies, thereby reducing patient morbidity. This technology is especially useful when professionals do not have access to computer navigation techniques, due to the high cost and limited availability of such equipment.^{4,5}

In recent years, 3D-printed drilling guides have been the subject of studies evaluating their advantages in pedicle screw fixation, particularly in patients with adolescent idiopathic scoliosis. Pedicle screws demonstrate great efficacy in rod fixation, providing rigidity and stability to curve correction. Freehand screw placement in these patients is a technically demanding procedure and is not immune to potential neurological complications.^{4,5,12}

With the aim of evaluating the safety and efficacy of patient-specific 3D-printed drilling guides for pedicle screw insertion, Senkoylu et al.¹² designed a study in which 11 patients aged between 12 and 18 years underwent preoperative CT, creating 3D bone models for each vertebra of each patient. The guides were modeled according to safe pedicle trajectories determined from the 3 planes of the models, and were subsequently printed in biocompatible material. After surgery, no screw-related injury was reported in vascular, neurogenic, or other vital structures. Furthermore, no complications related to screw placement occurred and no revision surgery was performed.¹²

The costs of the 3D guides were approximately €2 for each level-2 pedicle screw. For 10 pedicle screws inserted with alternating fixation for T4–T12 fusion, the total cost of the screw guides was €10. The authors describe that the reproducibility of the technique with the guides is robust and can be applied by less experienced spine surgeons.¹²

With the use of 3D guides compared to fluoroscopy- and CT-assisted intraoperative navigation systems, no additional preparation was required. With different navigation devices, some problems may occur, including synchronization issues, difficulty in landmark recognition, risk of device movement, and the need to keep looking at the screen while placing pedicle screws. With 3D guides, the surgeon can keep the focus on the surgical field.¹²

McLaughlin et al.⁴ also conducted a study to investigate the benefits and costs between screw insertion with printed guides and freehand screw placement in spinal fusion for the surgical treatment of adolescent idiopathic scoliosis. The study included 29 patients, of whom 18 used printed guides and 11 the freehand technique. The use of guides resulted in a higher cost of 3D-printed implants, with a mean of \$26,215 ± \$6,374, compared to freehand, with a mean of \$18,660 and standard deviation (SD) = \$5,587; however, there was a gain in terms of lower intraoperative blood loss with the use of 3D printing, with a mean of 357 mL, SD = 123, versus a mean of 559 mL, SD = 273, with the freehand technique.

When 3D guides were used, no pedicle screw required removal, unlike freehand-inserted screws, where some required removal and repositioning. The authors suggest that the guides may be a tool that contributes to the education and understanding of trainees, without compromising patient outcomes and safety.⁴

A review by Lopez et al.⁸ on preoperative planning with 3D-printed guides for pedicle screw placement in adults reports that, with the use of guides, mean surgical duration decreased from 272 to 258 minutes. It also notes that the manufacturing costs of the guides can vary significantly, depending on production time, printer type, and materials used.

Marginal costs range from US\$175 to US\$290, and the authors conclude that 3D-printed drilling guides for screw placement in the treatment of spinal deformities provide substantially greater accuracy and favorable deformity-correction rates compared with the freehand technique.⁸

Sheha et al.¹³ and Kumar et al.⁵ cite the study by Senkoylu et al.,¹² which reports spending between US\$12 and US\$28 per

vertebral level for the fabrication of drilling guides. Other types of 3D-developed and printed guides are osteotomy guides for pediatric and adult patients; they can be printed in titanium or polyamide, and the fabrication cost varies depending on the technology and material chosen, and may exceed US\$175.^{2,5,13}

With the use of customized 3D-printed guides, procedures were more efficient compared to the freehand technique, not only regarding screw positioning, but a lower intraoperative radiation exposure was also observed with the use of 3D printing: 0.23 millisievert [mSv] vs 0.82 mSv, since these surgeries are generally guided by fluoroscopy.^{2,5}

Beyond guides, it is possible to develop other objects that assist in screw insertion while maintaining the ideal trajectory. Ramirez et al.¹⁴ developed a retractor to improve surgeon comfort, facilitate visualization of reference landmarks, and identify the ideal entry point for pedicle screw insertion while maintaining the trajectory in transforaminal lumbar interbody fusion surgeries.

The retractor was printed using resin, with a total printing time of 3 hours. The cost of 1 liter of resin was estimated at approximately US\$185, with approximately 25 retractor units producible from that quantity. A single tool was tested on 20 patients, showing no wear after the surgeries. Furthermore, the radiolucency of the material allowed the use of the C-arm without moving the retractor during the procedures.¹⁴

Phantoms and simulators

In the context of medical learning for surgeries and procedures, observation and skills training are fundamental; however, training on patients, although essential, presents challenges such as patient discomfort and potential safety risks. Given this scenario, it becomes necessary to seek other training alternatives, such as the use of cadavers and phantoms.^{2,5,6,13,15}

For cadavers, training certain procedures is unfeasible due to preservation costs under ideal conditions ranging from US\$5,000 to US\$10,000, as well as biological hazard risks and availability. Another solution found was educational phantoms, developed by the industry from cadaveric molds. However, both phantoms and simulators require significant investment, with the maintenance cost of the latter being particularly high. For example, a model for lumbar puncture and spinal epidural training may cost approximately US\$4,000, with replacement lumbar region tissue costing US\$1,610.^{2,5,6,13,15}

With the aim of low-cost reproduction with accessible materials, 3D printing has proven a viable alternative for building this type of phantom.

In recent decades, companies have invested in optimizing materials that mimic the biomechanical properties of human bone, including flexion, torsion, and axial load. However, the availability of models that faithfully reproduce pathologies, deformities, and fractures designed for fluoroscopy use remains limited. As such, a group of professionals conducted a study to develop a phantom for training in normal and abnormal spinal surgery, 3D-printed from patient CT-derived images.¹⁵

The authors used FDM printers and two different materials to simulate cancellous and cortical bone: EasyFil (US\$34.30/kg) and EasyWood (US\$68.62/kg). The costs of the 4 vertebrae, supports, and an assembly plate were US\$11.46. This enabled reproduction of tactile properties during trocar insertion and ensured bone and spinal compatibility in imaging examinations such as fluoroscopy and conventional X-ray. The deformities and fractures present in the CT scans were also reproduced.¹⁵

Some spinal procedures, such as lumbar punctures, epidurals, and spinal blocks, are essential in hospitals. Simulators are used to improve the competencies of students and assistant physicians, thereby avoiding unnecessary patient discomfort. Due to the high cost of commercial simulators for ultrasound-guided puncture training, ODOM et al. (2019)⁶ developed a model that simulates a teaching spine, using ballistic gel to represent soft tissues, a latex tube, and a spine composed of 5 3D-printed vertebrae.

The total material cost for producing the model was \$30, and the preparation and printing time ranged from 30 to 60 minutes. The result was a customizable educational phantom that allows palpation, can be used with ultrasound as a guide, enables the simulation of complex anatomies, is easy to maintain and repair, and allows numerous attempts without compromising the trainee's experience.⁶

CONCLUSION

The analyzed literature reports that 3D printing has been successfully integrated into SS, employed in surgical planning, intraoperative surgical guides, and customized prostheses, and that its cost has decreased over the years. Furthermore, the data show that the use of this technology reduces overall costs by reducing operative

time, blood transfusion volume, and the more rational use of surgical materials, thereby avoiding waste.

The benefits of 3D printing in healthcare and SS are already recognized, given current and emerging applications. However, more robust studies are needed to thoroughly analyze, in the medium and long term, the full financial impact of 3D printing in SS in the Brazilian context.

Future studies should consider the technology used, printing time, and present and describe production costs and the possible cost-effectiveness of printing, its impact on time and materials in surgical planning, and others, so that it is possible to quantify how much 3D printing reduces costs, understand its benefits in depth, and analyze the impact of its contribution to the surgical process in Brazilian healthcare.

CONFLICT OF INTEREST

All authors declare no potential conflict of interest related to this article.

CONTRIBUTIONS OF THE AUTHORS

Each author contributed individually and significantly to the development of this article. FAPC: Data Curation, Investigation, Original Draft and Writing, Review & Editing; AALF: Original Draft and Writing, Review & Editing; SFAP: Data Curation; SM: Original Draft and Writing, Review & Editing; SVM: Investigation, Writing, Review & Editing; SN: Investigation, Writing, Review & Editing; AMAB: Writing, Review & Editing.

DATA AVAILABILITY DECLARATION

The data underlying the research text are available upon reviewer request.

REFERENCES

- Cai H, Liu Z, Wei F, Yu M, Xu N, Li Z. 3D Printing in Spine Surgery. *Adv Exp Med Biol*. 2018;1093:345-59. doi: 10.1007/978-981-131396-7_27.
- Tong Y, Kaplan DJ, Spivak JM, Bendo JA. Three-dimensional printing in spine surgery: a review of current applications. *Spine J*. 2020;20(6):833-46. doi: 10.1016/j.spinee.2019.11.004.
- Eltes PE, Kiss L, Bartos M, Gyorgy ZM, Csakany T, Bereczki F, et al. Geometrical accuracy evaluation of an affordable 3D printing technology for spine physical models. *J Clin Neurosci*. 2020;72:438-46. doi: 10.1016/j.jocn.2019.12.027.
- McLaughlin WM, Donnelley CA, Yu K, Gillinov SM, Tuason DA. Three-dimensional printing versus freehand surgical techniques in the surgical management of adolescent idiopathic spinal deformity. *J Spine Surg*. 2022;8(2):234-41. doi: 10.21037/jss-22-28.
- Kumar N, Ramakrishnan SA, Lopez KG, Chin BZ, Devyapriya S, Kumar L, et al. Current trends and future scope in 3D printing for surgical management of spine pathologies. *Bioprinting*. 2022;26:197-209. doi: 10.1016/j.bprint.2022.e00197.
- Odum M, Gomez JR, Danelson KA, Sarwal A. Development of a Homemade Spinal Model for Simulation to Teach Ultrasound Guidance for Lumbar Puncture. *Neurocrit Care*. 2019;31(3):550-8. doi: 10.1007/s12028-019-00779-4.
- Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. A declaration PRISMA 2020: diretriz atualizada para relatar revisões sistemáticas. *Rev Panam Salud Publica*. 2022;46:1. doi: 10.26633/RPSP.2022.112.
- Lopez CD, Boddapati V, Lee NJ, Dyrszka MD, Sardar ZM, Lehman RA, et al. Three-Dimensional Printing for Preoperative Planning and Pedicle Screw Placement in Adult Spinal Deformity: a systematic review. *Global Spine J*. 2020;11(6):936-49. doi: 10.1177/2192568220944170.
- Pacione D, Tanweer O, Berman P, Harter DH. The utility of a multimaterial 3D printed model for surgical planning of complex deformity of the skull base and craniocervical junction. *J Neurosurg*. 2016;125(5):1194-7. doi: 10.3171/2015.12.JNS151936.
- Goel A, Jankharia B, Shah A, Sathe P. Three dimensional models: an emerging investigational revolution for craniocervical junction surgery. *J Neurosurg Spine*. 2016;25(6):740-4. doi: 10.3171/2016.4.SPINE151268.
- Koper D, Laak-Poort MT, Lethaus B, Yamauchi K, Moroni L, Habibovic P, et al. Cranioplasty with patient-specific implants in repeatedly reconstructed cases. *J Craniomaxillofac Surg*. 2019;47(5):709-14. doi: 10.1016/j.jcms.2019.01.034.
- Senkoylu A, Cetinkaya M, Daldal I, Necefov E, Eren A, Samartzis D. Personalized Three-Dimensional Printing Pedicle Screw Guide Innovation for the Surgical Management of Patients with Adolescent Idiopathic Scoliosis. *World Neurosurg*. 2020;144:e513-22. doi: 10.1016/j.wneu.2020.08.212.
- Sheha ED, Gandhi SD, Colman MW. 3D printing in spine surgery. *Ann Transl Med*. 2019;7(Suppl 5):S164. doi: 10.21037/atm.2019.08.88.
- Ramirez MJE, Nurmukhametov R, Bernard E, Peralta I, Efe IE. A low-cost three-dimensional printed retractor for transforaminal lumbar interbody fusion. *Cureus*. 2022;14(4):e24185. doi: 10.7759/cureus.24185.
- Stefan P, Pfandler M, Lazarovici M, Weigl M, Navab N, Euler E, et al. Threedimensional-Printed Computed Tomography-Based Bone Models for Spine Surgery Simulation. *Simul Healthc*. 2020;15(1):61-6. doi: 10.1097/sih.0000000000000417.