Three-Dimensional Printing in Spinal Surgery: Current Uses

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LEARNING OBJECTIVES: After participating in this CME activity, the spine surgeon should be better able to:
1. Explain advantages of 3D printing in education and training.
2. Describe current uses of 3D printing for surgical instrumentation and spinal implants.
3. Identify potential benefits and drawbacks to use of 3D printing in spinal surgery.

Key Words: Additive manufacturing, 3D printing, Rapid prototyping, Solid free-form technology

Researchers have been studying the applications of 3-dimensional (3D) printing in spinal surgery for decades; however, clinical use of this technology remains in its infancy. With a growing emphasis on precision and customization among spine surgeons, 3D printing serves as a promising conduit for surgical teaching, preoperative planning, and the designing of tailored surgical instruments and implants. Despite the many benefits of this innovation, however, there are several factors limiting its widespread adoption among practicing spine specialists. We aim to examine the current uses of 3D printing and provide a case in support of implementation of this technology in both investigative and clinical applications.

3D printing is made possible via rapid prototyping (RP), also called additive manufacturing (AM) or solid free-form technology. During this process, layers of materials (ie, metal, plastic, powder, liquids, cells, etc) are applied sequentially to assemble a precise and highly detailed 3D anatomical representation. Although this technology has been used in orthognathic, abdominal, trauma, vascular, hand, pelvic, ankle, and several other surgery types, a substantial proportion of scientific studies on 3D printing in surgery are devoted to spinal procedures (nearly 8%). Prior literature has presented several uses of 3D printing in spinal surgery: (I) education, (II) assistance in presurgical planning, (III) surgical instrumentation, and (IV) spinal implants.

EDUCATION

Due to the ongoing evolution of spinal procedures, with many technological advancements in recent years, comprehensive education on innovative techniques has become essential for the formation of skilled spinal surgeons. Although cadavers represent realistic depictions of anatomy and are effective for surgical skills training for students and residents, they pose ethical and economic constraints, with limited availability. As such, modern methodologies including virtual reality and 3D printing are increasingly being introduced in anatomical education. Although the former has shown potential in decreasing the learning curve and improving visuospatial aptitude among neurosurgeons, high costs, limited availability, and need for additional training pose significant drawbacks to its incorporation into surgical education. In contrast, 3D printing represents a low-cost alternative that is more readily available. A shift toward lower prices and shorter production times has been reported in literature; 2 studies demonstrated an approximate cost of $10 for materials required to generate a 3D spine model. 3D printing has also repeatedly demonstrated satisfactory production of...
precise, anatomically detailed replicas of spinal structures.\textsuperscript{2} Mao et al\textsuperscript{18} reported improved anatomical visualization among 3D-printed models for deformity cases studied. Izatt et al\textsuperscript{19} illustrated superior anatomical depiction among 3D-printed constructs for deformity and tumor patients for 65\% of cases, whereas Zhao et al\textsuperscript{20} were able to use a detailed 3D-printed model to successfully compute the insertion angle for percutaneous tubular retraction during minimally invasive surgery of the thoracic spine.

Furthermore, Stefan et al\textsuperscript{15} created 3D-printed spine models from CT films using 2 separate substances for cortical and cancellous bone. Experienced surgeons then conducted vertebral body trocar placement on this model, confirming high reproducibility with realistic properties including comparable haptic feedback.\textsuperscript{15} The authors reported on the ability of 3D printing to effectively illustrate both benign and pathologic anatomy.\textsuperscript{15} Moreover, Clifton et al\textsuperscript{17} studied SpineBoxes, a minimal cost, 3D-printed learning tool, which demonstrated satisfactory visualization of bony anatomy under fluoroscopy and allowed for practicing of pedicle screw placement. Enhanced education to patients is an additional reported benefit of this technology, as 3D constructs may allow patients to better understand and visualize their diagnosis and intervention plan. One study reported that use of a 3D biomodel versus 2-dimensional (2D) image to explain existing disease and the proposed surgical plan resulted in 25\% higher informed consent scores (89\% vs 64\%).\textsuperscript{21}

Ultimately, with low associated costs, extensive availability, improving speeds, and a proven track record in detailing realistic spinal anatomy, aforementioned studies provide a convincing case for implementation of 3D printing in medical student and resident education and preoperative patient communication.

**PREOPERATIVE PLANNING**

As 3D-printed prototypes are able to accurately portray patient-specific pathology of the spine in a live, physical construct, surgeons may take advantage of this anatomically detailed model in the preoperative planning stages.\textsuperscript{2} Many complex spine cases (i.e., scoliosis) are not reliably visualized preoperatively with CT or MRI, in part due to intraoperative rotational changes and segmental or pedicle abnormalities less clearly depicted on 2D imaging. With the advent of precise 3D depictions of pathology, surgeons are able to mitigate such limitations and can experience invaluable tactile and haptic feedback that may better prepare them to circumvent obstacles during surgery.\textsuperscript{2} Jiang et al\textsuperscript{22} used a CT-based 3D-printed 1:1 model to stimulate surgery preoperatively for deformity patients with adult kyphoscoliosis. The authors concluded that this model could accurately represent individualized anatomy of the spine.
and its relationship to surrounding vertebrae, vasculature, and neural structures, and serve as an effective tool for generating patient-specific surgical plans for internal fixation, fusion, and orthopedic osteotomy.22

Barges-Coll et al23 studied a 3D biomodel of a cervical kyphoscoliosis patient and discovered additional locations of ankylosis not visualized on 2D films. Multiple-level osteotomy plans were then devised based on these newfound landmarks. The authors concluded on the usefulness of 3D printing in planning, stating its ability to offer greater surgeon understanding of a patient’s pathoanatomy before surgery. In a prospective observational study, Guarino et al24 studied the use of RP among challenging pediatric spine deformity cases and also demonstrated its benefit with preoperative planning, while also reporting improved safety and decreased operative times in 4 of 5 cases. Jug et al25 used individualized 1:1 3D models for pediatric spine cases, illustrating its value in practicing screw instrumentation preoperatively to decrease risk of adverse events and limit exposure to x-ray radiation (Figure 1).26 Mobbs et al27 similarly concluded satisfactory results in use of custom AM during presurgical planning of an anterior lumbar interbody fusion (ALIF) patient. Moreover, Xiao et al28 concluded that preoperative planning with AM before spinal tumor surgery helped determine tumor extent and localization of critical structures in proximity to the tumor.

Fox and Kanawati29 also created a 3D-printed spine model to facilitate surgical planning before tumor surgery and showed that it could enhance precision and safety (Figure 2). Although preoperative planning with RP may appear to entail greater financial burden, the subsequent likelihood of increased patient-specific anatomical knowledge, decreased operative time and blood loss, improved screw insertion accuracy, and recognition of aberrant anatomy not discernible on 2D imaging likely outweigh initial costs, providing strong evidence in favor of its use in spinal surgery.1,3,27,28,30 Nevertheless, more level I and II studies with larger sample sizes are required to enhance statistical quality and power and provide a greater understanding on the feasibility and utility of RP use in presurgical planning.

**SURGICAL INSTRUMENTATION**

Insertion of pedicle screws using free-hand (FH) technique has demonstrated considerable error, with one meta-analysis illustrating significantly higher accuracy rates among robot-assisted versus FH techniques.31 Molliqaj et al32 similarly reported higher rates of Grade A (of the Gertzbein-Robbins scale) screw insertion among robot-assisted (83%; 366 screws) versus fluoroscopy-assisted FH placement (76%; 335 screws), concluding FH may be a less safe and reliable method. Although FH screw malplacement has been reported to be >30% in prior literature, robotic and image-guided methodologies provide low rates of failure (3%–11%).33 The introduction of 3D-printed screw guides also offers promising results with regard to placement accuracy, offering error rates from as low as 2% to approximately 10%.34 Which is the better technique given similar malplacement rates? Although image-guided surgery and robot assistance provide remarkable accuracy, these techniques involve radiation exposure, imposing health risks to patients and staff.33 Children who undergo spine surgery may be more at risk as follow-up management often involves repeated radiation-based therapies.33 Complex deformity patients requiring revision procedures may also experience a greater burden of accumulated radiation exposure.33 With RP-constructed, patient-specific screw guides, accuracy may be optimized without transmitting radiation to patients and surgical staff.35

Ribera-Navarro et al35 concluded that, irrespective of surgeon experience, 3D-printed screw guides offer better accuracy and reliability versus FH insertion with the potential to reduce operative duration and incidence of postoperative adverse effects. Cecchinato et al34 additionally demonstrated superior outcomes among 3D-customized screw guides illustrating improved accuracy and lower radiation versus FH techniques among spinal deformity patients. Furthermore, several studies have reported satisfactory results for 3D-printed screw guide use for cervical transarticular and laminar screw insertion, thoracolumbar cortical screw insertion, and among congenital scoliosis patients for insertion throughout the entire spine.1,35-38
Additionally, 3D printing has provided satisfactory results in creating a drill template to ease through positioning and bone removal during expansive open-door laminoplasty.\(^4\) Overall, although 3D-constructed surgical tools clearly demonstrate promise in accuracy and safety, more randomized controlled trials on human subjects comparing these techniques with conventional methods are necessary to provide convincing evidence for widespread implementation.

**SPINAL IMPLANTS**

In generating a spinal implant, investigators aim to replicate the durability and porosity inherent to human bone. However, when porosity is optimized, osteoconductivity is compromised. Conventional implantable cages and devices may consist of varying composition of chemicals that contrasts that of bone, risking subsidence and cage migration.\(^4\) In contrast, RP technology can advantageously construct implantable devices that offer strength and porosity while preserving osteoconductivity of the hardware.\(^4\) 3D-printed implants offer the additional benefit of patient specificity: spine surgeons may no longer need to manipulate a patient’s existing anatomy, but can instead customize an implant to adapt to varying spinal morphology.\(^1\) This allows for preservation of the patient’s cortical bone and vertebral endplates and increased likelihood of reestablishing normal anatomy.\(^1\) Mobbs et al\(^27\) used a custom-fit interbody implant for an L5/S1 ALIF case, reporting decreased surgery time and improved fitting versus conventional interbody devices. The authors also commented on the possibility of patient-specific, custom implants to decrease blood loss, rapidly provide stability, and offer higher arthrodesis rates.\(^27\)

In an in vivo ovine lumbar fusion study, McGilvray et al\(^41\) demonstrated that, compared with polyetheretherketone (PEEK) and plasma sprayed porous titanium-coated PEEK (PSP) implants, 3D-printed porous titanium alloy (PTA) cages provided significantly more bony ingrowth within the cage space. This translated to superiority in biomechanical outcomes, as only the PTA cohort demonstrated significant reductions in flexion-extension range of motion and significant improvements in stiffness along each loading trajectory. Chung et al\(^42\) describe a wide vertebral defect caused by implantation failure of an expandable titanium cage for fusion after infection, which was corrected using a 3D-printed implantable device. Three years after this correction, the implant was in place with maintained bony arthrodesis, and there were no infectious or hardware-related adverse effects observed.\(^42\)

Osteotomy guides may also be constructed with 3D printing, with Tu et al\(^19\) observing >90% accuracy in screw placement among patients with severe kyphoscoliosis as a result of ankylosing spondylitis, with no significant injuries to major nerves or blood vessels. 3D-constructed osteotomy guides may also aid in tumor resection, with one study indicating its utility in removing an intraosseous chondrosarcoma of the sacroiliac joint.\(^1\) Additionally, 3D printing has provided satisfactory results in creating a drill template to ease through positioning and bone removal during expansive open-door laminoplasty.\(^40\)

Figure 2: Anterior (A) and posterior (B) views of the 3D-printed spine model used during preoperative planning, demonstrating location of nerves relative to the spinal structures and osteochondroma. Anterior (C) and posterior (D) views of the resected tumor. (From 3D Print Med. 2021;7(1):31. Licensed under Creative Commons license CC-BY 4.0 International License. http://creativecommons.org/licenses/by/4.0/.)
of 3D-printed implantable devices offers enhanced clinical and radiographic outcomes in various spinal surgery settings. However, as many studies on this topic are case reports and case series, more studies providing level I and II evidence are required to validate the favorable trends observed and strengthen an argument for broader-scale RP implant use.

CONCLUSION

Research and clinical application of 3D printing technologies remains in its nascent stages. Although existing literature provides support in favor of its application for education, preoperative planning, instrumentation engineering, and implant production, the majority of articles on this topic remain confined to level IV evidence. Thus, although results are likely promising for widespread implementation of this highly accurate, cost-efficient, and safe technology, further inquiry with high-quality studies consisting of larger sample sizes will provide a deeper, more intuitive understanding of its value in spine surgery.

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1. All of the following are established purposes of 3D printing in spine surgery, except:
   A. educating medical students and residents on spinal anatomy.
   B. providing a novel implantable device methodology catered only to experienced surgeons.
   C. enhancing patients’ understanding of their diagnosis and treatment before surgery.
   D. constructing pedicle screw guides for improved accuracy.

2. Which one of the following statements regarding pedicle screw misplacement is true?
   A. FH techniques are the least error-prone.
   B. FH screw malpositioning rates range from 3% to 11%.
   C. 3D-printed screw guides demonstrate decreased malpositioning rates compared with FH techniques.
   D. Robotic and image-guided methodologies may demonstrate misplacement in more than 30% of cases.

3. Surgical tools reproduced via 3D printing include:
   A. pedicle screw guides.
   B. osteotomy guides.
   C. drill templates.
   D. all of the above.

4. Most studies of 3D printing in spine surgery have a level of evidence of:
   A. IV.
   B. III.
   C. II.
   D. I.

5. 3D printing has applications in:
   A. cervical segments.
   B. thoracic segments.
   C. lumbar segments.
   D. all of the above.

6. 3D-printed spinal implants have applications in which of the following types of spine procedures?
   A. tumor
   B. congenital deformity
   C. prior implantation failure
   D. all of the above

7. Which one of the following is an important disadvantage to use of robotics and image guidance in pedicle screw placement versus 3D-printed screw guides?
   A. inferior accuracy
   B. radiation exposure
   C. higher failure rates
   D. higher availability

8. Disadvantages to use of cadavers instead of 3D printing for anatomic education include:
   A. higher cost.
   B. limited availability.
   C. ethical concerns.
   D. all of the above.

9. 3D printing applications are able to:
   A. calculate the insertion angle for tubular retraction during minimally invasive spine surgery.
   B. identify locations of ankylosis before surgery.
   C. evaluate tumor extent preoperatively.
   D. all of the above.

10. Use of RP allows construction of patient-specific screw guides that optimize accuracy without transmitting radiation to patients and surgical staff.
    A. true
    B. false