Advances and Outcomes of 3D-Printed Models in the Surgical Management of Congenital Scoliosis: A Comprehensive Review

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ABSTRACT

Background: Congenital scoliosis is a complex spinal deformity resulting from anomalous vertebral development during embryogenesis. Traditional surgical management poses significant challenges due to the intricate and highly variable anatomy encountered in these patients. In recent years, the emergence of three-dimensional (3D) printing technology has revolutionized the preoperative planning and intraoperative execution of complex orthopedic procedures, including congenital scoliosis correction. The utilization of patient-specific 3D-printed models enables detailed anatomical visualization, allows for preoperative simulation of surgical techniques, and facilitates communication among the surgical team, patients, and their families. This comprehensive review aims to analyze the current advances and clinical outcomes associated with the application of 3D-printed models in the surgical management of congenital scoliosis. The review systematically examines the role of 3D-printed models in enhancing surgical accuracy, reducing operative time, minimizing intraoperative complications, and improving patient outcomes. Recent literature is appraised to evaluate the efficacy and safety of these models compared to conventional techniques, highlighting key advances in 3D-printing technology, material biocompatibility, and model customization. Furthermore, the review discusses existing challenges, including cost, learning curve, and regulatory concerns, as well as future directions for research and clinical integration. In conclusion, the integration of 3D-printed models into the surgical workflow represents a significant advancement in the management of congenital scoliosis, offering potential improvements in patient-specific care, surgical precision, and educational value. However, further high-quality studies are required to fully elucidate the long-term benefits and cost-effectiveness of this innovative approach.

Keywords: Congenital Scoliosis, 3D-Printed Models, Surgical Management

INTRODUCTION

Congenital scoliosis, a spinal deformity resulting from vertebral malformations present at birth, poses considerable clinical challenges due to its anatomical complexity, heterogeneity, and association with other congenital anomalies. The intricate three-dimensional (3D) deformities and proximity to critical neural and vascular structures often make surgical correction technically demanding and fraught with risks. Despite advances in imaging and surgical techniques, conventional approaches may be limited by inadequate visualization, estimation errors, and difficulty in fully appreciating the spatial anatomy unique to each patient. The introduction of 3D-printing technology into the realm of spinal surgery represents a paradigm shift, allowing for the creation of patient-specific anatomical models that can be used for preoperative planning, intraoperative navigation, and educational purposes. While initial studies have demonstrated promising results, questions remain regarding the true impact of 3D-printed models on surgical outcomes, safety, and cost-effectiveness in the management of congenital scoliosis. The primary aim of this review is to provide a comprehensive analysis of advances and clinical outcomes associated with the use of 3D-printed models in congenital scoliosis surgery. We systematically examine how these models enhance understanding of complex anatomy, facilitate surgical planning, and contribute to improved perioperative outcomes. Additionally, the review identifies existing research gaps, such as limited large-scale clinical studies and standardized outcome measures, that need to be addressed to fully validate the integration of 3D-printed models in routine clinical practice. Through a critical appraisal of current literature, this review seeks to inform clinicians, researchers, and policymakers on the potential benefits, limitations, and future directions of 3D-printing in the surgical management of congenital scoliosis [1,2].

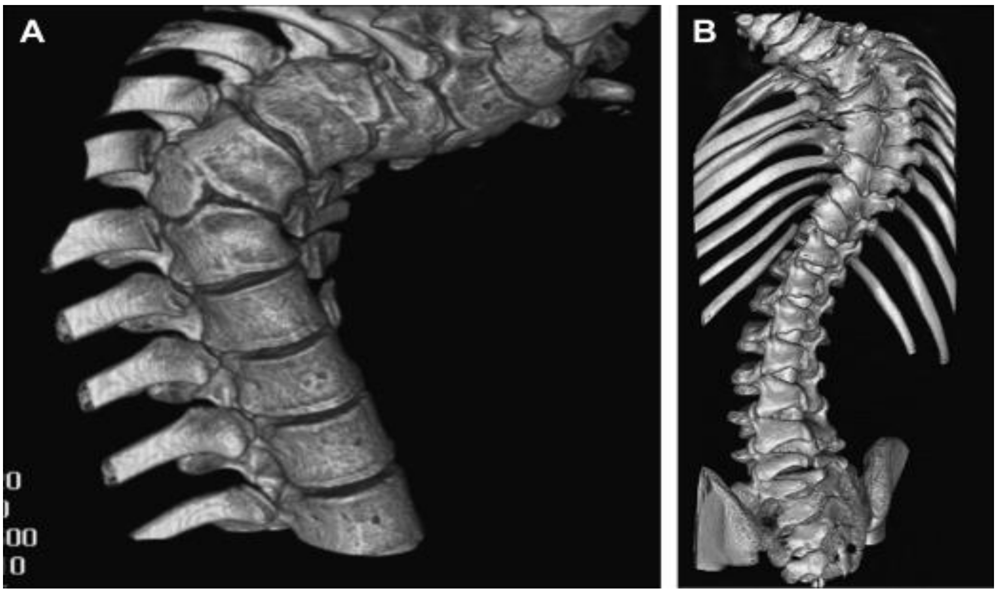

Figure (1) Three-dimensional reconstructions of computed tomography scans of 2 different patients with congenital scoliosis. (*A*) There is a failure of formation with a hemivertebrae visualized at the apex of deformity. (*B*) There is a failure of segmentation with unilateral bar and fused ribs at the apex of deformity

Overview of Congenital Scoliosis

Congenital scoliosis is a structural spinal curvature resulting from malformations of the vertebrae that occur during embryonic development. The incidence is estimated at approximately 1 in 1,000 live births, and it can present as either isolated vertebral anomalies or as part of syndromic conditions involving other organ systems. The underlying defects may include failures of vertebral formation (such as hemivertebrae), failures of segmentation, or mixed anomalies, all of which contribute to the diversity in curve patterns and progression rates seen in affected patients [3,4].

The pathophysiology of congenital scoliosis is rooted in disruptions to normal somitogenesis and chondrification processes during the first six weeks of gestation. This results in asymmetric vertebral growth, which may be further exacerbated by growth spurts during childhood and adolescence. The classification of congenital scoliosis is typically based on the type and location of the vertebral anomaly, as well as the presence of associated abnormalities in the ribs, spinal cord, or other organs. Early identification and thorough evaluation are crucial, as the risk of rapid curve progression and neurological complications is higher compared to idiopathic scoliosis [5,6].

Conventional surgical management of congenital scoliosis includes a spectrum of procedures, ranging from in situ fusion to complex osteotomies and vertebral resections. The goals of surgery are to halt curve progression, correct deformity, and prevent or address neurologic deficits. However, these procedures are technically demanding due to the variable anatomy and the presence of abnormal bony and soft tissue structures. Preoperative imaging, traditionally reliant on two-dimensional radiographs and computed tomography (CT), provides valuable information but often falls short in conveying the full complexity of three-dimensional deformities [7,8].

Recent advancements in medical imaging, including high-resolution CT and magnetic resonance imaging (MRI), have improved the ability to delineate bony and neural structures. However, these modalities still present challenges in preoperative planning, particularly in visualizing the surgical field and anticipating intraoperative obstacles. This underscores the need for adjunctive technologies that can bridge the gap between imaging and surgical execution, paving the way for the incorporation of 3D-printed models in the management of congenital scoliosis [9,10].

Introduction to 3D-Printed Models in Orthopedic Surgery

Three-dimensional (3D) printing, also known as additive manufacturing, has transformed the landscape of orthopedic surgery by enabling the production of patient-specific anatomical models, surgical guides, and even implantable devices. The process begins with high-resolution imaging, typically using CT or MRI scans, which are then converted into digital 3D models through specialized software. These models are subsequently printed layer by layer using materials such as resin, plastic, or metal, resulting in a tangible replica of the patient's anatomy [11,12].

The use of 3D-printed models in orthopedics was initially limited to complex reconstructive cases and tumor surgery. However, as the technology has become more accessible and affordable, its applications have expanded to include trauma, arthroplasty, and spine surgery. These models offer distinct advantages over conventional imaging by providing surgeons with a tactile, spatially accurate representation of bony and soft tissue structures. This hands-on approach enhances anatomical understanding, aids in preoperative planning, and allows for rehearsal of surgical procedures, potentially reducing intraoperative uncertainty and improving outcomes [13,14].

Beyond surgical planning, 3D-printed models have been utilized as intraoperative guides, assisting in the precise placement of implants and instrumentation. Their educational value is also significant, as they facilitate communication among surgical teams, trainees, and patients by providing a visual and physical reference. Furthermore, 3D printing has enabled the customization of prosthetic devices and implants tailored to individual patient anatomy, further advancing the concept of personalized medicine in orthopedics [15,16].

Despite these advantages, challenges remain regarding the widespread adoption of 3D printing in clinical practice. These include issues related to production time, cost, and the standardization of manufacturing processes. Regulatory approval for patient-specific devices also varies between regions, and there is an ongoing need for rigorous validation of model accuracy and clinical impact. Nevertheless, the expanding role of 3D printing in orthopedic surgery is reshaping the field and holds particular promise for the management of complex deformities such as congenital scoliosis [17,18].

Role of 3D-Printed Models in Congenital Scoliosis Surgery

The integration of 3D-printed models into the surgical management of congenital scoliosis has ushered in a new era of precision medicine, particularly for anatomically complex and variable deformities. One of the primary benefits of these models is their utility in preoperative planning, where they provide a three-dimensional, patient-specific visualization of vertebral anomalies, spinal alignment, and associated rib or neural structures. Surgeons can manipulate these models to better understand the intricacies of the deformity, simulate osteotomies, and strategize the most effective surgical approach, thereby minimizing intraoperative surprises and reducing the likelihood of complications [19,20].

During surgery, 3D-printed models serve as valuable intraoperative guides. They enable accurate localization of bony landmarks and facilitate the safe placement of pedicle screws and other hardware, which is especially critical in malformed or dysplastic vertebrae. Some centers have also reported the use of sterilizable 3D-printed templates for guiding instrumentation, improving the accuracy of screw placement and reducing the risk of neural or vascular injury. These advances are particularly important in pediatric patients, where the margin for error is small and the consequences of malposition can be severe [21,22].

In addition to surgical planning and guidance, 3D-printed models enhance communication among the multidisciplinary team, including orthopedic surgeons, anesthesiologists, radiologists, and nursing staff. The ability to visualize and discuss the precise anatomy fosters a collaborative approach to care and facilitates anticipation of intraoperative challenges. These models also serve as effective educational tools for residents and fellows, allowing them to gain hands-on experience with complex spinal deformities outside the operating room [23,24].

Furthermore, 3D-printed models have been shown to improve patient and family engagement by providing a tangible representation of the deformity and proposed surgical intervention. This can lead to improved understanding, reduced anxiety, and more informed consent. Collectively, the integration of 3D-printed models in congenital scoliosis surgery represents a significant step toward individualized, precise, and safer surgical care [25,26].

Figure (2). It is a 44-year-old congenital scoliosis female patient. 3DP spine model was made to assist the pre-operative plan making, intraoperative screw implantation and osteotomy at the apex vertebrae

Recent Advances in 3D-Printing Technology for Spinal Surgery

Recent years have witnessed substantial progress in 3D-printing technology as applied to spinal surgery, with significant implications for the management of congenital scoliosis. Advances in imaging resolution, segmentation software, and printing techniques now allow for the creation of highly accurate and detailed models that faithfully replicate complex spinal and rib anatomy. These technological improvements facilitate more precise preoperative planning and increase surgeon confidence in navigating atypical anatomical features [27,28].

The range of materials used in 3D printing has also expanded, with options including biocompatible plastics, resins, and even metals. High-fidelity materials mimic the texture and mechanical properties of cortical and cancellous bone, enabling surgeons to practice osteotomies, screw insertion, and other procedures on realistic models before entering the operating room. Such hands-on rehearsal not only enhances technical preparation but may also shorten the learning curve for less experienced surgeons or those confronted with particularly challenging cases [29,30].

Customization is another key advance, as current software can incorporate patient-specific data to tailor models according to the precise anatomy and pathology of each case. This allows for the simulation of different surgical strategies, such as various osteotomy levels or hardware configurations, thereby optimizing operative plans. Additionally, 3D-printed templates and guides can be designed to fit unique anatomical landmarks, ensuring accurate placement of implants or resections in real time during surgery [31,32].

Beyond model accuracy and customization, some research groups have begun integrating augmented reality (AR) and virtual reality (VR) platforms with 3D printing to provide immersive visualization and intraoperative navigation. The combination of these technologies is poised to further enhance surgical precision and safety. Despite these advances, challenges persist regarding scalability, speed of model production, and integration into routine clinical workflows. Ongoing collaboration between engineers, radiologists, and surgeons is essential to drive further innovation and clinical adoption [33,34].

Clinical Outcomes and Evidence

Multiple clinical studies and case series have evaluated the impact of 3D-printed models on surgical outcomes in congenital scoliosis, providing a growing body of evidence supporting their utility. One of the most consistent findings is the improvement in surgical accuracy, particularly in the placement of pedicle screws and other spinal instrumentation. Several reports have documented reduced rates of screw misplacement and neurological complications when 3D-printed models or guides are used, compared to traditional freehand or fluoroscopy-guided techniques [35,36].

Operative time and intraoperative blood loss are also commonly reported outcome measures. Studies have shown that the use of 3D-printed models enables more efficient surgical planning and execution, resulting in shorter operative times and reduced blood loss. This is likely due to better anticipation of anatomical challenges, more precise instrumentation, and the ability to simulate complex procedures preoperatively. These improvements are particularly valuable in pediatric patients, who are at higher risk for complications associated with prolonged anesthesia and excessive bleeding [37,38].

Additionally, the rate of intraoperative and postoperative complications appears to be lower in surgeries utilizing 3D-printed models. Reports indicate fewer instances of hardware malposition, unplanned returns to the operating room, and neurological deficits, underscoring the models' role in enhancing surgical safety. Surgeon-reported satisfaction and confidence are also higher, with many clinicians citing increased preparedness and reduced intraoperative stress as key benefits of model use [39,40].

Patient and family satisfaction is another important outcome, as the tangible models facilitate clearer communication and better understanding of the planned procedure. In several studies, families expressed greater confidence in the surgical team and a higher level of comfort with the process when 3D-printed models were used during preoperative discussions. While most published evidence consists of retrospective series and small prospective studies, the trend toward improved clinical outcomes is promising and warrants further exploration in larger, controlled trials [41,42].

Overall, while limitations remain in the quality and scale of available evidence, the integration of 3D-printed models into the surgical management of congenital scoliosis has been associated with measurable improvements in accuracy, safety, efficiency, and patient engagement. Continued research is needed to validate these findings and determine the long-term impact on patient outcomes [43,44].

Challenges and Limitations

Despite the many benefits associated with the use of 3D-printed models in congenital scoliosis surgery, several challenges and limitations have hindered their widespread adoption. One of the primary obstacles is cost; the production of high-quality, patient-specific models requires advanced imaging, specialized software, and 3D-printing materials, all of which can be expensive. For many healthcare systems, particularly in resource-limited settings, these additional costs may not be justified without clear evidence of significant clinical and economic benefits [45,46].

Production time is another significant limitation. Even with streamlined workflows, generating a 3D-printed model can take several days, from image acquisition and segmentation to printing and finishing. This timeline may not be compatible with urgent cases or settings where rapid surgical intervention is required. Efforts are ongoing to develop faster printing technologies and more efficient processes, but time constraints remain a barrier in routine practice [47,48].

The learning curve associated with 3D modeling and printing is also considerable. Surgeons and support staff must acquire new skills related to image segmentation, digital modeling, and interpretation of printed models. Variability in model accuracy, depending on operator expertise and software limitations, can affect the reliability of the models for surgical planning. Interdisciplinary collaboration between surgeons, radiologists, and engineers is essential to optimize model quality and clinical usefulness [49,50].

Technical limitations persist as well, particularly in reproducing soft tissue structures, neural elements, and microanatomy relevant to complex spinal deformities. Most models primarily depict bony anatomy, which, while useful, may not capture all aspects required for comprehensive surgical planning. Additionally, sterilization and intraoperative handling of 3D-printed guides or templates require careful consideration to maintain safety and efficacy [51,52].

Finally, regulatory and ethical considerations must be addressed. There is currently a lack of standardized guidelines for the clinical use of 3D-printed medical devices, and approval processes can vary significantly by region. Ensuring patient data privacy during model creation and sharing, as well as maintaining rigorous quality control standards, are vital for the responsible integration of this technology into clinical practice [53,54].

Conclusion

The integration of 3D-printed models into the surgical management of congenital scoliosis marks a significant advancement in orthopedic practice, providing tangible improvements in preoperative planning, intraoperative precision, and multidisciplinary communication. These patient-specific models allow surgeons to visualize and rehearse complex procedures, leading to more accurate instrumentation, reduced operative time, and lower rates of complications. The enhanced anatomical understanding and improved patient engagement further underscore the value of this technology in clinical care.

Although current evidence—largely derived from retrospective case series and small prospective studies—suggests substantial benefits, important challenges must still be addressed before widespread adoption can be realized. High production costs, lengthy fabrication times, and the need for specialized training represent significant barriers, particularly in resource-limited settings. Additionally, the absence of standardized regulatory frameworks and the technical limitations in reproducing soft tissue structures highlight areas for continued development.

As 3D printing technology continues to evolve, with improvements in speed, accuracy, and material diversity, it is expected that its clinical applications will broaden and become more cost-effective. Collaborative efforts among engineers, surgeons, and policymakers will be essential to optimize model production, establish best practice guidelines, and ensure patient safety. Future research should focus on large-scale, prospective studies to further define the long-term impact, cost-effectiveness, and patient-centered outcomes associated with the use of 3D-printed models in congenital scoliosis surgery.

In summary, 3D-printed models hold great promise as a transformative adjunct in the management of congenital scoliosis. With ongoing innovation and research, their routine clinical adoption may become a reality, offering improved precision, safety, and individualized care for affected patients.

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