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Review Article

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Utilization of 3D Printed Models in the Surgical Intervention of Spinal Deformities

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Abstract

Three-dimensional printing technology offers the potential to amend patient care and decrease costs in a variety of surgical specialties, including spine surgery. The benefits of 3DP have been demonstrated in numerous studies, however these studies are often underpowered and questions remain about its efficacy, cost and patient outcomes, particularly in the treatment of adult spinal deformity. Hence, in this review, our objective was to investigate inquiries pertaining to the effectiveness, cost, and patient outcomes, particularly in the treatment of spinal deformities using three-dimensional printing, taking into account the age and gender of the patients. Three-dimensional printing (3DP), likewise known as additive manufacturing or rapid prototyping, is an increasingly popular technology in healthcare with the potential to enhance patient care and reduce costs. By creating prototypes of customizable shapes from 3D software renderings using a range of materials such as polystyrene, nylon, titanium and stainless steel, 3DP can assist surgical planning, improve anatomic visualization, design custom prosthetics, facilitate procedural rehearsal and enhance doctor-patient communication. In conclusion, the use of 3D printing in spinal deformity cases can reduce surgical time, improve precision, and enhance patient outcomes for all genders.

Keywords: Spinal Deformity, 3D printing, osteotomy, pedicle screw

Introduction

Spinal deformity, a condition caused by congenital dysplasia, vertebral infections, trauma, or spinal tumors, can result in a variety of debilitating symptoms such as pain, difficulty in movement, severe spinal stenosis and even paralysis [1, 2]. Surgical intervention is often the primary treatment option, but due to the complex nature of the condition, orthopedic spine surgeons face significant challenges when attempting to correct spinal deformities [3]. Despite their importance in restoring and stabilizing spinal curvature, pedicle screws can cause significant harm to the spinal cord and surrounding neural tissues when placed using conventional methods due to the deformed pedicle anatomy associated with spinal deformity [4]. Several techniques have been developed to address this challenge, including the free-hand technique, screw placement with intraoperative fluoroscopic navigation, and three D-printed plate navigation [5, 6]. Although, the free hand technique is frequently challenging for surgeons to master and is associated with a

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low success rate of pedicle screw insertion, with reported accuracy ranging from 28% to 94% [7]. While computer-navigated surgery has been demonstrated to effectively increase the success level of pedicle screw insertion, its widespread implementation has been constrained by its high cost [8]. However, recent advancements in 3D data reconstruction and personalized 3D printing technology have sparked growing interest in the potential of utilizing 3D printing to aid in surgical planning [9, 10]. Multiple studies have demonstrated that 3D printing technology has the capacity to not only reduce surgical time but also enhance the precision of pedicle screw placement. Nevertheless, the current body of research on the application of 3D printing in spinal deformity correction surgeries remains limited [11-13]. In this review, an attempt was made to analyze and compare various treatment aspects based on age, gender, and cost-effectiveness as reported in published studies.

Spinal deformity & 3D printing technology

Spinal deformities can arise from various factors, including congenital defects, injury, and other medical conditions [14, 15]. Traditionally, fully comprehending the precise anatomy and pathology of the affected area through conventional imaging techniques has been challenging for surgeons [16]. However, the emergence and advancement of 3D printing technology have alleviated these challenges. Surgeons now have the capability to utilize 3D printing to create precise spine models that accurately depict the anatomy and pathology of the affected area, facilitating more precise surgical planning and execution [17]. While computed tomography (CT) scans and reconstructed images have conventionally been employed for evaluating spinal deformities, the utilization of 3D printed models has been found to provide surgeons with a more comprehensive understanding of the intricate skeletal anatomy [18]. Comparative to reconstructed 3D-rendered images, the use of 3D printed models has demonstrated a significant enhancement in the quality of surgical planning. The precision of 3D printed models in accurately representing relevant anatomy can assist surgeons in identifying structural abnormalities that may not be easily discernible in 2D CT images [19]. This capability contributes to more precise surgical planning and improved outcomes. Multiple studies have documented the use of intraoperative navigation systems and robotic-assisted systems to enhance the accuracy of pedicle screw placement in the treatment of degenerative spinal conditions and certain deformities. While these systems have demonstrated effectiveness in specific cases, their application in severe spine deformity surgery has been constrained by inadequate evidence and practical challenges [20-22]. In contrast, 3D printing technology has emerged as a cost-effective and practical alternative for the treatment of severe spinal deformities [23]. These printed models have the capacity to simulate a wide array of clinical scenarios, including rare or complex situations that are challenging to replicate in real-life scenarios. Additionally, these models can be crafted from materials that replicate the density, hardness, and flexibility of human tissues, thereby providing a realistic training environment for surgeons [17].

Unlike cadaveric training, 3D printed models can be readily produced on demand, eliminating the need for expensive and often scarce cadavers. This makes 3D printing a more practical and cost-effective option for surgical training [24]. In the context of complex spinal deformities, 3D printed models serve as valuable learning tools for junior doctors [25]. Research conducted by Zhao et al. demonstrated that training junior surgeons with 3D printed models significantly enhances their ability to accurately place pedicle screws, with all surgeons achieving independent accuracy after six months of training [26]. Furthermore, numerous studies have highlighted the capacity of 3D printed models to enhance surgical education, facilitate communication among surgical teams, and improve patients' comprehension of their condition and the planned surgical procedures [9].

Applications of 3DP

Screw-Drill Guides

In general, the utilization of 3DP screw-drill guides and preoperative surgical models has demonstrated a significant reduction in operative duration and increased accuracy of screw placement when compared with non-3DP techniques, including freehand placement. While there was no significant difference in intraoperative blood loss between 3DP and non-3DP techniques, the overall association of 3DP technology with positive surgical outcomes was evident in the reviewed studies. These findings strongly indicate that 3DP technology can serve as a valuable tool for enhancing the efficiency and effectiveness of spinal deformity correction surgeries [27, 28].

Presurgical Planning

In general, 3DP technology has proven to be valuable in presurgical planning, particularly in complex spinal deformity cases. The majority of the reviewed studies have indicated that 3DP planning models offer enhanced visualization of spinal anatomy and improved understanding of the associated bony architecture, surpassing non-3DP techniques. These benefits are likely to contribute to more efficient surgery and increased deformity correction rates. While some studies have noted an increase in hospital costs with the use of 3DP, the potential advantages of 3DP in presurgical planning are promising and warrant further exploration [29]. The studies not only indicated a lack of apparent benefit in employing 3DP technology in presurgical planning but also highlighted increased hospital costs compared to non-3DP cases [30]. This finding contrasts with the majority of the other reviewed studies, which have reported favorable outcomes with the use of 3DP in presurgical planning [10, 27]. Nevertheless, further investigation is essential to gain a better understanding of the potential impact of 3DP on surgical planning and costs [31, 32].

Training and Education

The use of 3DP technology has shown promising potential in the areas of surgical training and education, communication among surgical team members, and patients' education and communication. Studies have indicated that 3DP models can enhance understanding of patient anatomy, improve procedural guidance, and boost trainee confidence [33]. Additionally, 3DP has been demonstrated to facilitate improved patient communication and satis-

faction during pre-surgical consultations by providing clear and tangible representations of complex anatomy and imaging. These findings underscore the growing importance of 3DP in enhancing various aspects of spine surgery [34, 35].

Production Process of 3DP

A variety of 3D printing technologies were utilized in the studies under review. The most commonly used technology was stereolithography (SLA), which was utilized in over half of the studies (56%). The second most common technology was selective laser sintering (SLS), including selective laser melting (SLM) and MySpine technologies, which was used in 37.5% of the studies. The least common technology was fused deposition modeling (FDM), which was only used in 12.5% of the studies (Table. 1).

Table. 1: Categories of 3D printing.

Category	Technology Types	Number of Studies
Most Common	Stereolithography (SLA)	18 out of 32 (56%)
Second Most Common	Selective Laser Sintering (SLS)	12 out of 32 (37.5%)
Least Common	Fused Deposition Modeling (FDM)	4 out of 32 (12.5%)

The costs, production lead times, and materials used in the reviewed studies varied significantly. The set of screw drill guides typically costs an average of $415 and has an average production lead time of 5.8 days. Additionally, 3DP planning tools are priced at an average of $1263 with an average production time of 4.9 days. The average cost for 3DP applications used in training and education was $1673, with an average production time of 8.6 days (Table. 2). A variety of materials were used in the 3DP processes, with polymers being the most commonly used material in 75% of the studies. The most commonly used polymers were polystyrene and resin, which were both used in 17% of the studies. Titanium or stainless steel was used in 16% of the studies for 3DP templates or implants (Table. 3).

Table. 2: Average Cost of 3D printing.

Category	Technology Types	Number of Studies
Application	**Average Cost**	**Average Production Lead Time**
Screw Drill Guides	$415	5.8 days
Planning Tools	$1263	4.9 days
Training and Education	$1673	8.6 days

Table. 3: Material Type of 3D printing.

Material Type	Number of Studies
Polymers	24 out of 32 (75%)
Metals	5 out of 32 (16%)
Synthetic Bone Graft Materials	N/A
Other	N/A
Most Common Polymers	**Number of Studies**
Polystyrene	5 out of 32 (17%)
Resin	5 out of 32 (17%)

These findings demonstrate that while 3DP technology has significant potential in the field of spinal surgery, there is a wide range of options available in terms of technology, cost, lead time and materials. It is important for surgical teams to consider these factors when deciding which 3DP technology to use for specific applications [27, 28].

Advantages for severe spinal deformity surgery

The incredible adaptability of 3D printing technology enables the development of intricate training models, providing numerous benefits for severe spinal deformity surgery.

First, 3D-printed spine models play a pivotal role in enhancing surgeons' understanding of the complex anatomical structure of the surgical site. These models serve as valuable tools for surgical rehearsal, ultimately accelerating the learning curve for surgeons and significantly elevating the standard of clinical education [36].

Second, the precision offered by 3D-printed models results in improved screw placement accuracy, thereby reducing the need for extensive fluoroscopy exposure during the surgical procedure. This

advancement significantly contributes to enhanced surgical safety standards [37].

Third, the integration of 3D printing technology in surgical planning has the potential to streamline operation times, leading to increased surgical efficiency and improved patient outcomes [21].

Patient Age Group (Pediatric, Adult, Elderly)

Spinal deformities can manifest across all age groups, with variations in the type of deformity and corresponding treatment depending on the patient's age. The needs of pediatric patients, for instance, may differ significantly from those of adult or elderly patients when it comes to corrective surgery. The successful utilization of 3D printing technology across all age groups is evidenced by its capacity to generate personalized, patient-specific models, empowering surgeons to meticulously strategize and execute surgeries with heightened precision and efficacy [38, 39].

Treatment Method

Traditional methods for treating spinal deformities have historically involved open surgery and diagnostic imaging techniques such as X-rays and CT scans [15]. However, the rapid integration of 3D printing technology is revolutionizing the approach to spinal deformity treatment. Surgeons can now utilize intricate 3D printed models to gain a comprehensive understanding of the patient's unique spinal anatomy, meticulously plan surgical interventions, and even simulate complex procedures on the models before performing the actual surgery. This innovative application holds significant promise for enhancing patient outcomes and mitigating the inherent risks associated with traditional open surgery [40].

Outcomes

The utilization of 3D printing technology in spinal deformity surgery has been demonstrated to yield a range of favorable outcomes [17, 35], including:

- Enhanced surgical precision: The implementation of 3D printed models enables surgeons to meticulously plan and rehearse surgical procedures, resulting in heightened accuracy and a reduced incidence of complications.
- Improved surgical efficiency: Through the utilization of 3D printed models, surgeons are able to efficiently strategize and simulate surgeries, leading to decreased operation times and minimized patient discomfort.

Table 4 provides a concise summary of the application of 3D printing technology in diverse patient age groups affected by various spinal deformities, along with the potential associated outcomes. It is important to note that specific details may vary based on individual cases and contextual factors.

Table. 4: Summary of the application of 3D printing technology in diverse patient age groups.

Patient Age Group	Type of Spinal Deformity	Treatment Method	Outcomes
Pediatric	Congenital, Idiopathic	3D printing, Traditional	Improved accuracy, safety, and patient satisfaction with 3D printing; traditional methods also effective but may have longer operative times
Adult	Idiopathic, Degenerative	3D printing, Traditional	Improved efficiency, safety, and cost-effectiveness with 3D printing; traditional methods may have longer recovery times
Elderly	Degenerative	3D printing, Traditional	Improved safety and patient satisfaction with 3D printing; traditional methods may have higher complication rates

The patient's gender

Table 5 demonstrates the cost-effective application of 3D printing technology in spinal deformity surgery for various patient groups, including different genders. It has been observed that tailored implants offer a cost-effective solution for male patients with degenerative scoliosis, whereas precise surgical planning and patient-specific models can result in long-term cost savings for female patients with adolescent idiopathic scoliosis [27]. Additionally, the adoption of 3D printing in spinal trauma cases has the potential to minimize costs for patients of all genders by reducing surgical duration, enhancing precision, and ultimately improving patient outcomes [41, 42].

Table. 5: The cost-effective application of 3D printing technology in spinal deformity surgery.

Patient Group	Type of Spinal Deformity	3D Printing Application	Cost-Effectiveness
Male	Degenerative Scoliosis	Customized implants	Reduced overall costs due to shorter surgery time, fewer complications, and improved patient outcomes
Female	Adolescent Idiopathic Scoliosis	Surgical planning, patient-specific models	Initial setup costs, but long-term cost savings due to improved accuracy and reduced revision surgery rates
All Genders	Spinal Trauma	Surgical planning, surgical guides	Cost effective for complex cases, as it reduces surgery time, enhances accuracy, and improves patient outcomes

Discussion

Patients with severe spinal deformities require surgical intervention to address their condition. However, the intricate nature of their spinal anatomy can make the insertion of pedicle screws a difficult procedure (43-45).

Utilizing 3D printing technology allows surgeons to anticipate potential complications before the procedure, thus facilitating preoperative surgical planning and simplifying the surgical process for patients with severe spinal deformities [46, 47].

The customized full-scale 3D-printed spine models allow for precise analysis of the patient's surgical anatomy, thereby permitting the development of more effective and safer surgical approaches for osteotomy and screw placement in patients with severe spinal deformities [48, 49].

The utilization of precise 3D printing in spinal surgery can enhance preoperative planning, reduce the complexity and duration of surgery while improve patient outcomes in cases involving severe spinal deformities [50, 51].

Precise 3D models allow surgeons to plan and rehearse a safe surgical corridor or approach prior to surgery, thus reducing the complexity of the procedure and shortening the operating time for intricate cases involving severe spinal deformities [52-54].

Abudunaibi Aili et al conducted a study in which they utilized 3D-printed models in the preoperative planning of spinal deformity. The results showed a significant reduction in operating time, intraoperative hemorrhage, and x-ray exposure when using 3D-printed spinal deformity models. The researchers first constructed 3D models, and then reconstructed the anatomical relationships between the deformed segments of the spine to directly evaluate the severity of deformity [55].

At the next stage, building on these 3D models, the researchers then determined the position, direction and depth of pedicle screw placement, pre-bent the connecting rods, and planned the location and method of osteotomy. This 3D model-based planning for screw placement, osteotomy, and bone fusion reduced excessive trauma and hemorrhage from excessive exposure during surgery, allowing more time for accurate osteotomy and screw placement. These findings are consistent with those of Garg et al., who also found that 3D printing-aided surgery can significantly reduce intraoperative time, x-ray exposure, hemorrhage, and achieve more accurate screw placement compared to the control group [56].

Past studies have also reported that preoperative planning using 3D-printed spinal deformity models can not only reduce operation time and hemorrhage, but also increase the correction of Cobb's angle, thereby alleviating symptoms associated with spinal deformity in patients [42].

In the study by Abudunaibi Aili et al, correction of both thoracic and lumbar regions at coronal and sagittal plane Cobb's angles was significantly higher in the experimental group, where 3D-printed models were used, compared to the control group [55].

Contrary to the improved Cobb's angle correction, no difference in VAS pain scores and ODI scores was observed between the two groups, despite significant improvements in both parameters after surgery and throughout follow-up. This may be due to patients in both groups achieving satisfactory recovery after surgery, as final VAS and ODI scores were both significantly improved [55, 57].

Tan et al. reported findings that indicated 3D-printed model-assisted surgical planning significantly increased the accuracy of screw placement and efficacy of deformity correction, while reducing the incidence of surgery-related complications [58].

In a study conducted by Li and colleagues, 3D printing technology was employed to develop models of the cervical spine in 22 patients with deformities. Surgeons utilized these models to simulate posterior cervical operations, enabling precise determination of screw placement routes and angles. The simulations led to improved screw accuracy and a notable absence of vertebral artery injuries [59].

In another investigative study, 3D printing technology was utilized to aid in the treatment of 16 patients with severe scoliosis. Surgeons employed 3D printed models of the patients' spines to simulate the surgical procedure prior to the actual operation, allowing for precise determination of optimal screw placement angles and depths [60].

Accurate implantation of pedicle screws in deformed spines presents a formidable challenge for surgeons due to factors including vertebral rotation, thin pedicles, hemivertebrae, unsegmented vertebrae, or multi-segment fused vertebrae. This study compared the outcomes of patients with severe spine deformities who underwent posterior pedicle screw fixation and fusion with the guidance of 3D printed models (3DP group) and without (free-hand group). The results revealed that pedicle screw placement was more accurate and operation time was significantly reduced with the use of 3D printed models [42, 61]. Patients with severe spine deformities often necessitate spinal osteotomies for optimal correction, but these procedures carry increased risk as the complexity of the osteotomy increases. Traditionally, the surgeon plans the osteotomy based on their knowledge of spinal anatomy, but the use of 3D printed models has been shown to enhance the accuracy of bone resection and decrease operative time in orthopedic surgery [61].

Pan et al. advocate for the integration of 3D printed models into the workflow of severe spinal deformity surgery. They assert that 3D printing technology holds significant potential for widespread use in orthopedics, with possibilities for rapid advancement in the medical 3D printing industry [42].

However, the authors acknowledge several limitations to their study, including a relatively small sample size, non-random patient selection for the control and 3D printing groups, and a lack of analysis on the correlation between misplaced screws and the primary pathology of the deformity. They intend to conduct further research to address these limitations [42, 51, 62].

Although 3D printing technology holds significant promise for improving surgical planning in the treatment of spinal deformities, its present high cost and limited accuracy serve as impediments to widespread adoption [32, 63]. However, as the quality of 3D print-

ers and printing materials continues to advance and their cost decreases, it is foreseeable that these limitations will be surmounted, paving the way for broader utilization of this technology in the future [64, 65].

While previous studies have highlighted the advantages of utilizing 3D-printed spine models in the surgical planning of spinal deformities, they are not without limitations. The retrospective nature of these studies may introduce bias in patient selection, despite the absence of significant differences in preoperative patient demographics and deformity severity between the two groups [27, 42, 51]. Future prospective studies are imperative for establishing more robust evidence of the beneficial effects of employing 3D-printed spine models. Additionally, the single-center design and relatively small sample size in these studies constrain their generalizability. Therefore, to validate the findings of previous research and extend their applicability to a broader population, the need for multi-center studies with larger sample sizes becomes increasingly evident. Such studies are essential for providing more substantial evidence of the benefits associated with using 3D-printed spine models in the surgical planning of spinal deformities.

Conclusion

It is essential to thoroughly investigate the effectiveness, costs, and patient outcomes associated with using three-dimensional printing (3DP) for the treatment of spinal deformities. This investigation will take into account the age and gender of the patients. Three-dimensional printing, also known as additive manufacturing or rapid prototyping, is an increasingly popular and innovative technology in healthcare. It has the potential to significantly improve patient care and reduce healthcare costs. In conclusion, the utilization of 3D printing in spinal deformity cases has shown promising results, such as reducing surgical time, enhancing precision, and improving patient outcomes for individuals of all genders.

Conflict of Interest Statement

The authors declare that they have no conflicts of interest related to this work. No financial, personal, or professional relationships influenced the research, writing, or submission of this manuscript.

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