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Three-Dimensional Printing for Preoperative Planning and Pedicle Screw Placement in Adult Spinal Deformity: A Systematic Review

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Abstract

Study Design: Systematic review.

Objectives: This current systematic review seeks to identify current applications and surgical outcomes for 3-dimensional printing (3DP) in the treatment of adult spinal deformity.

Methods: A comprehensive search of publications was conducted through literature databases using relevant keywords. Inclusion criteria consisted of original studies, studies with patients with adult spinal deformities, and studies focusing on the feasibility and/or utility of 3DP technologies in the planning or treatment of scoliosis and other spinal deformities. Exclusion criteria included studies with patients without adult spinal deformity, animal subjects, pediatric patients, reviews, and editorials.

Results: Studies evaluating the effect of 3DP drill guide templates found higher screw placement accuracy in the 3DP cohort (96.9%), compared with non-3DP cohorts (81.5%, $P < .001$). Operative duration was significant decreased in 3DP cases (378 patients, 258 minutes) relative to non-3DP cases (301 patients,272 minutes, $P < .05$). The average deformity correction rate was 72.5% in 3DP cases (245 patients). There was no significant difference in perioperative blood loss between 3DP (924.6 mL, 252 patients) and non-3DP cases (935.6 mL, 177 patients, $P = .058$).

Conclusions: Three-dimensional printing is currently used for presurgical planning, patient and trainee communication and education, pre- and intraoperative guides, and screw drill guides in the treatment of scoliosis and other adult spinal deformities. In adult spinal deformity, the usage of 3DP guides is associated with increased screw accuracy and favorable deformity correction outcomes; however, average costs and production lead time are highly variable between studies.

Keywords
three-dimensional printing, 3D printing, rapid prototyping, additive manufacturing, spine surgery, adult spinal deformity, deformity correction

Introduction

The use of 3-dimensional printing (3DP) technology, also known as additive manufacturing or rapid prototyping, is rapidly expanding in health care and has the potential to improve patient care and reduce costs. It offers the ability to create prototypes of customizable shapes from 3D software renderings using a variety of different materials. Across surgical specialties, 3DP technology has been shown to be beneficial in aiding surgical planning, enhancing patient education and resident training, improving intraoperative navigation, and reducing operative durations.[1,2]

Three-dimensional printing technology involves using computed tomography (CT) or magnetic resonance imaging (MRI)

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to create a digital 3D model that is then sliced into 2D sections, which are physically produced in layers by a 3D printer and eventually fused into a final model.[3] Different materials are used in the printing process—stereolithography (SLA) most commonly involves the use of polystyrene or resin, whereas selective laser sintering (SLS) employs a focused energy source on various materials such as nylon, titanium, or stainless steel to sculpt a final model.[3] Another 3DP type, fused deposition modeling (FDM), creates layers using a heat-softened polymer. For complex surgical procedures such as spinal surgery, 3DP offers valuable preoperative planning and close anatomic guidance to avoid damaging nerves and vessels, which may improve patient outcomes.[4] Three-dimensional printing has shown utility across various surgical specialties, including spine surgery, in preoperative planning, anatomic visualization, custom prosthetic design, procedural rehearsal, and even as an educational tool for training and doctor-patient communication.[1,2,5-15]

New applications of 3DP in spine surgery have been described in the literature and their efficacy has been studied, but many studies are often single-institution and underpowered and questions remain about variable costs, production times, materials, and patient outcomes, especially in applications for treating adult spinal deformity.[7,16] The purpose of this review is to identify and evaluate all current applications of 3DP in the literature for the treatment of adult spinal deformity and to assess surgical outcomes with and without the utilization of 3DP.

Methods

Search Strategy and Information Sources

A comprehensive search of publications (up to November 2019) was conducted using the EMBASE, Medline, and PubMed databases in accordance with PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. Search terms included the following keywords or MeSH terms: "3D printing," "three-dimensional printing," "rapid prototyping," "additive manufacturing," "scoliosis," "idiopathic scoliosis," "degenerative scoliosis," "kyphosis," "spinal deformity," "spine malformation," and "spine surgery" Boolean operators (OR, AND) were also used to maximize the sensitivity of the search.

Eligibility Criteria

Inclusion criteria consisted of original clinical studies, including studies that evaluated the feasibility and utility of 3DP technologies in the planning and/or treatment of adult scoliosis and other spinal deformities, studies evaluating the use of 3DP implants in spinal surgery, and studies with patients who present with scoliosis or other spinal deformities such as kyphosis in adult patients (>18 years old). Exclusion criteria consisted of studies that do not evaluate the use of 3DP technology in spine surgery, studies with nonscoliosis or nonkyphosis patients, animal subjects, or pediatric patients, non-English studies, inaccessible articles, reviews, and editorials. No limits were placed on level of evidence or timing of the study, since the majority of the reviewed studies were published within the past 10 years.

Study Selection

Article titles and abstracts were screened initially by 2 reviewers, and full-text articles were subsequently screened based on the selection criteria. The studies were rated by their level of evidence, based on the Oxford Centre for Evidence-based Medicine Levels of Evidence.[17] The reference list of all articles included in the study was also carefully assessed to identify any potential studies that may have been missed by our initial search strategy. Discrepancies in inclusion studies were discussed and resolved by consensus.

Data Extraction

A database was collected from all included studies with the following information: publication author and publication year, country of origin, study design, level of evidence, study duration, blinding of the study, number of involved institutions, 3DP technology type, production materials, production cost and time, pathology being treated, 3DP clinical application, primary and secondary outcome measures, result, sample size, average patient age, percent male patients, number of screws used (if applicable), screw accuracy rate, operative duration, blood loss, fluoroscopy utilization/exposure, preoperative and postoperative Cobb angles, percent deformity correction, reported intraoperative or postoperative complications, and any additional pertinent findings from the study. Articles were sorted into 3 different, non–mutually exclusive categories based on 3DP use/application (screw drill guides, presurgical planning, and training/education). Descriptive statistics were employed to summarize important findings and results from the selected articles and to describe trends in 3DP technology applications, materials, costs, and clinical outcomes. Post-surgical outcomes with and without the use of 3DP technology were assessed using weighted averages of patient cohorts across different studies, and with the use of Student's t test or Fisher's exact test for statistical significance testing. Significance was defined as $P < .05$. Data summarizing 3DP technology types, materials, costs, and production times were presented using simple averages, frequencies, and proportions.

Results

Search Results and Study Selection:

Using our predefined search terms resulted in 204 articles, of which 92 duplicate articles were removed. The remaining 112 articles were screened by title and abstract according to inclusion and exclusion criteria. Ultimately, there were 39 articles included for full review, of which 32 studies (with a total of 703 patients) met full inclusion and exclusion criteria (Figure 1). Seven articles were excluded during the full-review process

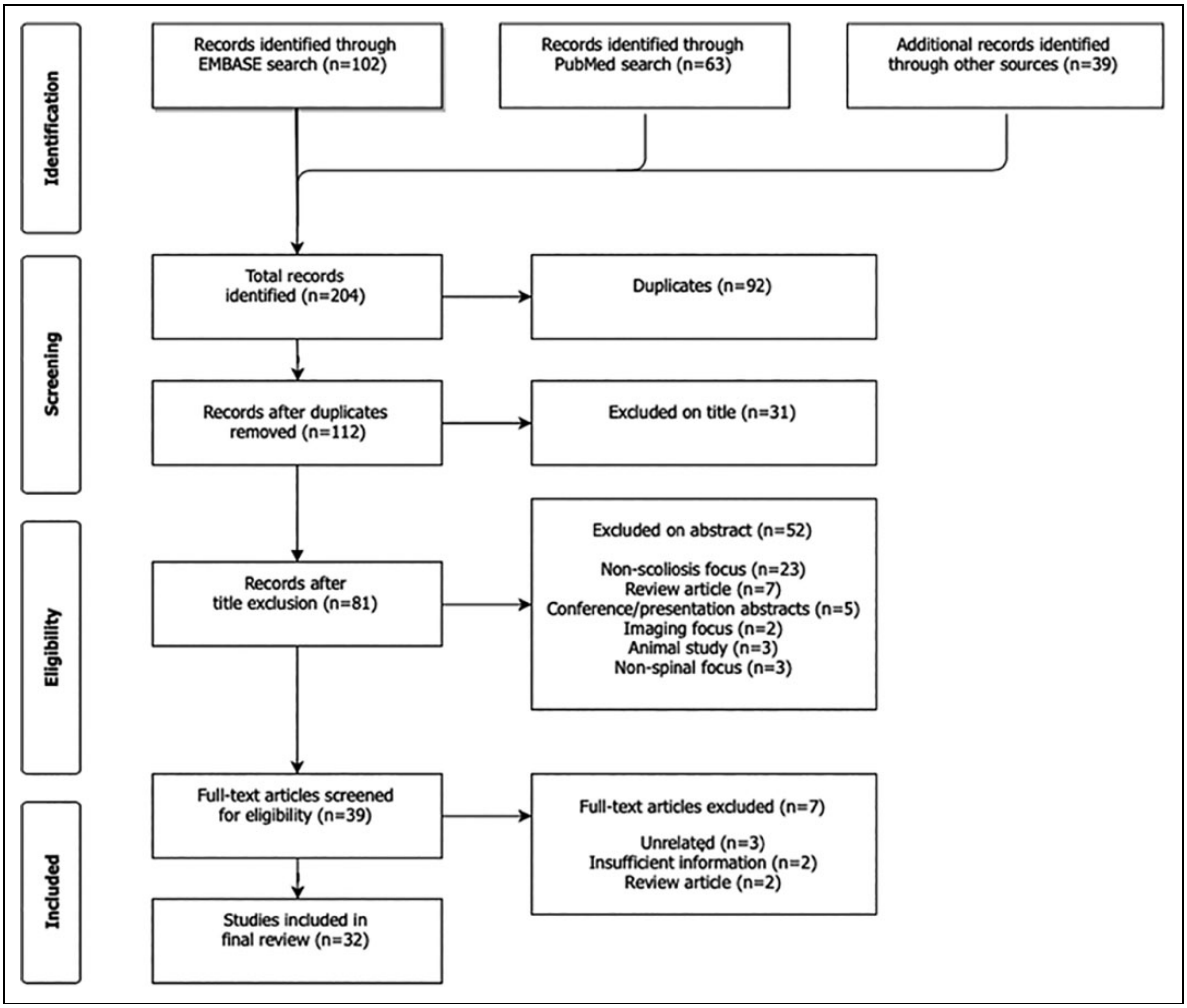

Figure 1. PRISMA flow diagram of included studies.

because they either violated exclusion criteria or did not have a focus on 3DP or spine surgery.

Applications

Screw Drill Guides. A total of 22 out of 32 reviewed studies (68.8%) evaluated the efficacy of 3DP drill guide templates in surgical treatment of spinal deformities (Table 1, Figure 2) Nine of eleven studies that assessed operative duration as an outcome variable found significantly decreased operative durations when 3DP screw drill guides were used, compared with cases in which no 3DP guides were used (free-hand, navigation-based, or imaging-based screw placement). Six studies compared 3DP guides with free-hand screw placement, 3 studies compared with navigation-based, and 2 studies compared with fluoroscopic guidance. Ten studies did not specify a comparison technique. Across these studies, the average operative duration decreased from 272 minutes in cases without a 3DP screw guide (301 patients) to 258 minutes with a 3DP screw guide (378 patients), which was statistically significant ($P < .05$). Three studies also reported significantly reduced intraoperative blood loss when using 3DP drill guides, compared to cases without 3DP. However, across 10 studies measuring blood loss, there was no significant difference in intraoperative blood loss between 3DP (177 patients, 925 mL) and non-3DP spine cases, after controlling for operating time and procedure type (252 patients, 936 mL, $P = .058$). Screw placement accuracy, confirmed with imaging, was also a commonly assessed outcome in studies assessing 3DP screw drill guides and preoperative surgical models. In 17 studies using 3DP screw drill guides or planning models, there was a significant increase in screw placement accuracy in the 3DP cohorts (96.9% of total screws placed), compared with non-3DP cohorts (81.5% of total screws placed; $P < 0.001$), including freehand placement (81.6%) and nonspecified techniques (81.3%). Screw placement accuracy was not reported for fluoroscopic-guided or navigation-based techniques.

Presurgical Planning. Twenty reviewed studies (62.5%) evaluated the use of 3D printing applications (ie, spine models, anatomical guides) in presurgical planning (Table 2, Figure 3). One of these studies concluded that not only did there not appear to be a benefit to using 3DP, but it also increased hospital costs compared to non-3DP cases (Chinese Yuan to USD

Table 1. Summary of 3DP Screw Drill Template Studies.

Study	3DP type	Comparison	Improvement in screw placement accuracy	Reduced operating time	Reduced blood loss	Reduced radiation exposure	% Mean deformity correction	Screw placement accuracy >90%	Complications	3DP beneficial result	Conclusions/results
Wang YT et al, 2016	SLS	Fluoroscopic guidance	—	Y	Y	—	90.9	—	None	Y	Photosensitive resin models can guide the drilling of pedicle screws during surgery. No pedicle penetrations or screw misplacement occurred.
Pijpker et al, 2018	SLA	—	—	—	—	—	70.3	—	None	Y	Assisted by 3D-printed individualized osteotomy-guiding templates, the kyphosis was successfully reduced with satisfactory correction of the kyphoscoliosis.
D'Urso et al, 2005	SLA	Navigation based	—	Y	—	—	—	Y	None	Y	Accurate screw placement was confirmed with postoperative CT scanning. Operating time was reduced, as less reliance on intraoperative radiograph was necessary.
Yang et al, 2015	SLS	Free hand	N	Y	Y	—	59.5	N	None	Y	There did not appear to be a benefit to using this technology with regard to complication rate and postoperative radiological outcomes; however, 3D technology could reduce the misplacement rate in patients whose preoperative mean Cobb angle was >50°. Besides, it also increased the patients' hospital cost.
Mohar et al, 2015	SLA	—	—	—	—	—	—	Y	None	Y	The guidance aid of specific rapid prototyping 3D templates shows high accuracy of the thoracic pedicle screw placement in spinal deformities.
Liu et al, 2017	SLA	Free hand	Y	Y	—	—	67.1	Y	None	Y	With the application of multilevel template, incidence of cortex perforation in severe and rigid scoliosis decreased and 3DP is, therefore, potentially applicable in clinical practice.
Azimifar et al, 2017	SLA, FDM	—	Y	—	—	—	—	Y	None	Y	The proposed template significantly reduced screw misplacements, increased stability, and decreased the sliding & the intervention invasiveness.
Zhang et al, 2017	FDM	Navigation based	—	Y	—	—	70.5	Y	None	Y	3DP-assisted selective segmental pedicle screws can obtain accurate, safe, and perfect outcomes in the treatment of scoliosis through improving the correction rate and shortening the operation time.
Pan et al, 2018	SLA	Free hand	Y	N	—	—	55	Y	None	Y	The drill guide template technique has potential to offer more accurate and thus safer placement of pedicle screws than free-hand technique in the treatment of severe scoliosis.
Tan et al., 2018	SLA	–	Y	–	–	–	–	Y	None	Y	3D-printed spinal model aids free-hand pedicle screw insertion in patients with complex spinal deformity. It can help spine surgeons to better understand and visualize the complex and altered spinal anatomy in severe spinal deformity.

(continued)

Table 1. (continued)

Study	3DP type	Comparison	Improvement in screw placement accuracy	Reduced operating time	Reduced blood loss	Reduced radiation exposure	% Mean deformity correction	Screw placement accuracy >90%	Complications	3DP beneficial result	Conclusions/results
Cecchinato et al, 2019	SLS	Free hand	Y	N	—	Y	—	Y	None	Y	Patient-specific, 3D-printed pedicle screw guides increase safety in a wide spectrum of deformity conditions by reducing significantly the incidence of pedicle screw malpositioning compared with the standard free-hand technique, and it reduced the intraoperative exposure to radiation and the surgical time of the implantation phase. However, the production time (4-6 weeks) is significantly longer than other 3DP studies.
Luo et al, 2019	SLA	Free hand	Y	Y	—	—	63	Y	1	Y	Accuracy of the surgical technique using spinal 3D printing combined with pedicle guider technology in patients with severe congenital scoliosis was higher than the accuracy of the free-hand technique. In addition, it appeared to shorten operative time.
Lu et al, 2012	SLA	Fluoroscopic guidance	—	Y	—	Y	71.1	Y	None	Y	3DP template significantly reduces the operation time and radiation exposure for the members of the surgical team, making it a practical, simple, and safe method. The potential use of a navigational template to insert thoracic pedicle screws in scoliosis is promising, and successfully reduced the perforation rate and insertion angle errors, demonstrating clear advantage in safe and accurate pedicle screw placement of scoliosis surgery.
Takemoto et al, 2016	SLM	—	—	—	—	—	—	Y	None	Y	This study provides a useful design concept for the development and introduction of patient-specific navigational templates for placing pedicle screws.
Otsuki et al, 2016	SLM	—	—	—	—	—	—	Y	None	Y	Using 3DP guides, all screws were inserted correctly without any complications, and can be applied not only in primary spine-surgery cases but also in revision surgeries.
Zhang et al, 2018	SLA	—	—	—	—	—	54.2	—	None	Y	Segmental pedicle screw instrumentation was performed under 3-dimensional printing assistance.
Garg et al, 2019	FDM	Free hand	Y	Y	Y	Y	—	Y	None	Y	Developing these patient-specific drill templates will enable spine surgeons to treat deformities with ease and safety.
Putzier et al, 2017	SLS	—	—	—	—	—	91	Y	None	Y	Custom-made positioning guide is a feasible navigational tool that permits a safe and accurate implantation of pedicle screws in patients with severe scoliosis.

(continued)

Table 1. (continued)

Study	3DP type	Comparison	Improvement in screw placement accuracy	Reduced operating time	Reduced blood loss	Reduced radiation exposure	% Mean deformity correction	Screw placement accuracy >90%	Complications	3DP beneficial result	Conclusions/results
Sugawara et al, 2013	SLA	Navigation based	—	Y	—	Y	—	—	None	Y	The multistep, patient-specific screw guide template system is useful for intraoperative pedicle screw navigation in the thoracic spine. This simple and economical method can improve the accuracy of pedicle screw insertion and reduce the operating time and radiation exposure of spinal fixation surgery.
Wang D et al, 2016	SLM	—	—	—	—	—	—	—	None	Y	Compared with the traditional technology of screw insertion, the use of the surgical metal template enabled the screws to be inserted more easily and accurately during spinal surgery.
Mokawen et al, 2019	SLM	—	—	—	—	—	—	—	None	Y	SiCaP-packed 3D-printed lamellar titanium cages provided excellent rates of solid fusion in TLIF and LLIF surgeries with notable improvements in patient-reported outcomes.
Marengo et al, 2019	SLS	—	—	—	—	Y	—	N	None	Y	The patient-matched guide for posterior CBT screw placement could improve placement accuracy and decrease the risk of nerve damage.

Abbreviations: 3DP, 3-dimensional printing; SLA, stereolithography; SLS, selective laser sintering; SLM, selective laser melting; FDM, fused deposition modeling; TLIF, transforaminal lumbar interbody fusion; LLIF, lateral lumbar interbody fusion; Y, yes; N, no.

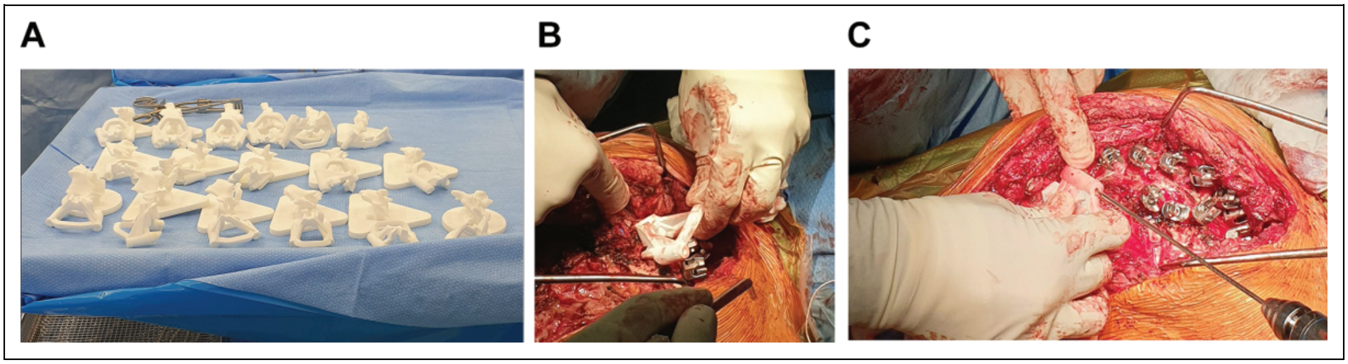

Figure 2. Sample images of custom 3D printed pedicle screw guides. Figure A shows sterile, back table preparation of all 3D printed guides for a specific patient, B shows one specific guide being placed at planned instrumented level, C shows a pedicle tract being drilled with orientation provided by the custom 3D printed guide. All figures were provided courtesy of Medacta International MySpine (Memphis, TN).

conversion: \$22 342 + \$1415.16 vs \$21 701 + \$1629, $P = .03$).[1] However, the other 19 reviewed studies found 3DP planning models to offer benefits to both attending and resident spine surgeons during presurgical planning in terms of enhancing understanding of spinal anatomy and associated bony architecture, especially in preparation for complex surgeries. In one of the studies, attending surgeons remarked that "anatomical details were better visualized on the 3DP models than on any imaging modalities."[18] Several studies reported favorable clinical outcomes when using 3DP technology—among 12 reviewed studies using 3DP planning models or 3DP drill guides, the reported average deformity correction rate was 72.5% in 3DP cases of 245 patients. Surgical time averaged 236 minutes, which was significantly less than the average surgical time of non-3DP studies (262 minutes; $P < .001$). Five total studies reported reduction in fluoroscopy exposure in cases using 3DP drill guides and/or planning models with an average radiation exposure decrease of 61.2%, although it was statistically non-significant ($P = .109$). Two studies measured fluoroscopy doses in cases with 3DP (average 30 unique images) and without 3DP (average 77 unique images).[19,20] One study in the review reported an intraoperative complication after using 3DP for presurgical planning, involving a patient who had a cerebrospinal fluid leak involving the nerve root axilla which was repaired with sutures.[21]

Training and Education. There were 7 reviewed articles (21.9%) which studied the use of 3DP in applications involving surgical training and education, communication between surgical team members, and patient education and communication (Insert Table 3). Surgical time averaged 257 minutes, although surgical time for non-3DP applications were not reported. Authors of studies analyzing 3DP applications in these settings cited enhanced preoperative understanding of patient anatomy by surveyed attending surgeons, resident trainees, and patients, as well as procedural guidance and improved trainee confidence as some of the most significant reasons for supporting the use of 3DP.[21-27] In addition, several studies reported improved patient communication and satisfaction during presurgical consultations by providing easy-to-understand and tactile 3DP renderings of complex anatomy and imaging.[18,21-23,28,29] Surgeons cited the benefits of 3DP models as helpful communication tools by "providing patients with a better appreciation of their condition, details of the planned surgical procedure, and the subsequent risks involved."[18] Surgeons and patients surveyed by Wang et al[28] stated that the tactile 3DP models enhanced intuitive understanding of the complex spinal anatomy and improved patient-surgeon communication.

3DP Production Process (Production Materials, Costs, and Time)

Numerous 3DP technology types were used in the reviewed articles. However, stereolithography (SLA) was the most commonly used 3DP technology, appearing in 18 out of 32 (56%) studies. Selective laser sintering (SLS), which also included selective laser melting (SLM) and MySpine technologies, was the second most commonly used 3DP technology, with 12 out of 32 studies (37.5%) reporting its use. Only 4 out of 32 studies (12.5%) used fused deposition modeling (FDM), which was the least used 3DP technology.

There are a wide range of reported costs (ranging from \$175 for a 3DP template model to \$5,400 for sophisticated 3DP spinal phantom training models), production lead time (9 hours to 1 month), and materials (polymers, metals, synthetic bone graft materials, other) (Table 4). The average cost for a set of screw drill guides was \$415, without including cost of the 3D model, with an average production lead time of 5.8 days. 3DP planning tools cost an average of \$1263, and production time averaged 4.9 days. 3DP applications for training and education purposes had an average cost of \$1673 and production time of 8.6 days. Various types of 3DP materials were used in the reviewed studies, with 15 different materials across 4 categories (metals, polymers, synthetic bone graft materials, and other). Polymers were reported as the most commonly used material type in 24 out of the 32 studies (75%). Polystyrene

Table 2. Summary of 3-Dimensional Printing (3DP) Presurgical Planning Studies.

Study	Primary outcome measure(s)	Secondary outcome measures	Improved presurgical planning	Conclusions/results
D'Urso et al, 2005	Accurate screw placement, operating time, patient surveys	—	Y	The biomodels were found to be highly accurate and of great assistance in the planning and execution of the surgery.
Coote et al, 2019	Clinical outcomes, patient satisfaction	Operating time, blood loss, complications	Y	3D models can not only improve preoperative planning and provide opportunities to rehearse for complex procedures, but they can also improve consultations with patients.
Guarino et al, 2007	Surgeon questionnaire responses	Operating time	Y	Provides significant benefits for complex surgeries of the pediatric spine and pelvis in the areas of preoperative planning, intrasurgical navigation, and communication with patients. A reduction in operating time may also be expected for cases of congenital scoliosis/kyphosis. However, production costs may vary, ranging up to $2500.
Yang et al, 2011	Screw placement accuracy, operating time, blood loss, deformity correction	Complications/implant failures	Y	Beneficial for preoperative planning and intraoperative reference and allows satisfactory correction of complex thoracic deformities.
Mao et al., 2010	Postoperative scoliosis Cobb angle	Complications	Y	Compared to spinal radiography, CT, MRI, and even 3D spinal reconstruction, the computer-designed polystyrene model served as a more tactile visual aid to confirm the positions of anatomical landmarks, helping the surgeon plan the operation and improve the accuracy of pedicle screw insertion.
West et al, 2014	Imaging	—	Y	3DP ultrasound phantom models that are derived directly from patient anatomy have strong potential as preprocedural planning tools in cases involving pathologies, implants, or abnormal anatomies.
Kim et al, 2016	Bone union/clinical outcomes	—	Y	Preoperative 3D printing was useful for understanding the bony architecture and nonunion.
Mobbs et al, 2017	Bone union/clinical outcomes	Operating time, blood loss	Y	3DP models can ease the difficulty of complex spinal surgery and shorten procedure time.
Izatt et al, 2007	Surgeon survey results about imaging	Operating time	Y	Surgeons stated that the anatomical details were better visible on the 3DP biomodel than on other imaging modalities and reduced operating time by a mean of 22% in deformity procedures. However, cost is high, ranging from $900 to $1500.
Wang YT et al, 2016	Operating time, blood loss	Complications (screw misplacement, pedicle penetration)	Y	The tactile models from 3D printing allow direct observation and measurement, helping orthopedists to have accurate morphometric information to provide personalized surgical planning and better communication with the patient and coworkers.

(continued)

Table 2. (continued)

Study	Primary outcome measure(s)	Secondary outcome measures	Improved presurgical planning	Conclusions/results
Pijpker et al, 2018	Kyphosis correction/clinical outcomes	—	Y	3DP planning model facilitated a detailed preoperative evaluation, greater insight into the case-specific anatomy, and accurate planning of the required correction.
Yang et al, 2015	Operating time, blood loss, postoperative hemoglobin, postoperative complications, and length of hospital stay.	Radiographic assessment of screw placement, postoperative Cobb angle, coronal balance, sagittal vertical axis, thoracic kyphosis, and lumbar lordosis	N	There did not appear to be a benefit to using this technology with respect to complication rate and postoperative radiological outcomes; it also increased the patients' hospital cost.
Mohar et al, 2015	Screw placement accuracy	Screw position/ trajectory	Y	After screw position was planned, 3D printing of a biocompatible template, the average difference in trajectory between planned and actual screw showed high accuracy of the thoracic pedicle screw placement in spinal deformities.
Zhang et al, 2017	Screw placement accuracy	Deformity correction, complications	Y	The placement site, direction and length of pedicle screws were consistent with those in 3D printing model. Cobb angle of major thoracic curve after operation were significantly improved compared with preoperation ($P < .05$), without nerve, blood vessel, or visceral injuries.
Wang H et al, 2017	Screw placement accuracy, bony healing	Operating time, blood loss, complications	Y	3DP technology can increase the accuracy and safety of operation, and can be provide more detailed preoperative, intuitive, three-dimensional, realistic personalized operation scheme. It can reduce the operation trauma and achieve rapid recovery after operation.
Lu et al, 2012	Screw Placement Accuracy	Operating time, radiation exposure	Y	Provides capability to preoperatively prepare and customize the surgical plan based on the unique morphology of each patient's pedicle. This method significantly reduces the operation time and radiation exposure for the members of the surgical team.
Tan et al, 2018	Screw placement accuracy	Operating time, blood loss, complications/ screw misplacements	Y	The 3D-printed spinal model is a helpful tool for surgical planning and freehand pedicle screw insertion in patients with complex spinal deformity. It can help spine surgeons to better understand and visualize the complex and altered spinal anatomy in severe spinal deformity.
Garg et al, 2019	Screw violation	Surgical time, blood loss, radiation exposure (number of shots required)	Y	3DP model successful in determining and planning the proper pedicle screw trajectory.
Putzier et al, 2017	Screw placement accuracy	Deformity correction, clinical complications	Y	The preoperative planning process, specialized algorithms to create patient-matched vertebral models, and guides for treating asymmetric and severely rotated vertebrae with small pedicles positively impact the surgeon, the patient, and the hospital team.
Marengo et al, 2019	Screw placement accuracy	Complications/screw misplacements/pedicle penetration	Y	The use of 3DP devices for cortical bone trajectory (CBT) fixation allows not only a customized plan but could also improve placement accuracy and decrease the risk of nerve damage. Furthermore, the need of fluoroscopy could potentially be set down to zero.

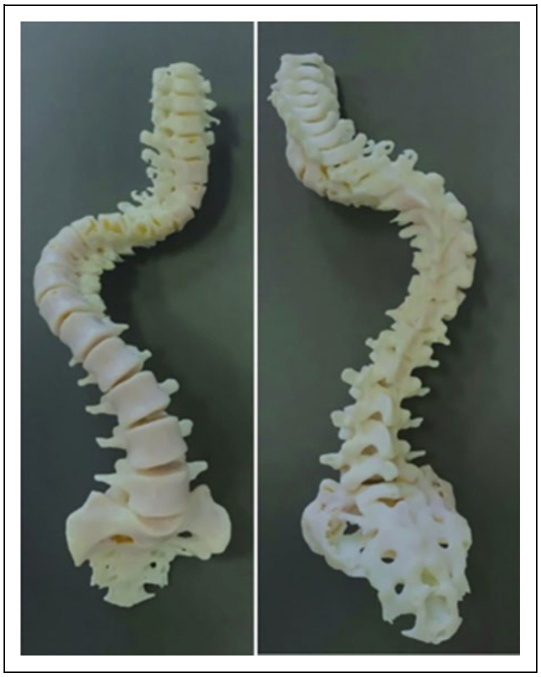

Figure 3. 3-Dimensional printed model of complex kyphoscoliosis.

and resin were both reported as the most commonly used polymers; each was used in 5 studies (17%). Titanium or stainless steel for 3DP templates or implants were used in 5 out of 32 (16%) studies.

Discussion

This systematic review evaluated current applications of 3DP in the surgical treatment of adult spinal deformities. The surgical treatment of scoliosis and other complex adult spinal deformities involves inherent difficulties such as anatomic anomalies, dysmorphic or absent pedicles, and vertebral rotation. These challenges make it difficult to visualize the scoliotic spine and its anatomical landmarks for pedicle screw insertion. As such, 3DP applications in the surgical planning process can aid spine surgeons in visualizing and understanding spine anatomy, enabling more detailed planning and simulation of the procedure, and instrumentation decisions.[4,18,23-25,30] Compared with a previous systematic review of 3DP in spine surgery,[4] our review focuses on the use of 3DP in treating adult spinal deformities, which poses unique challenges and opportunities. In addition, an increasing trend in the number of annual 3DP review—over one-third of the articles in this review (11 studies) were published in 2018 or 2019—makes it necessary to provide a more up-to-date review that includes the most current applications.

In our review, 3DP applications, including 3DP screw guides and planning models, have resulted in statistically decreased operative durations and increased pedicle screw placement accuracy.[1,18,19,28,31] Compared with conventional imaging (eg, intraoperative fluoroscopy), 3DP screw placement guides provide improved screw placement accuracy rates,[19,20,31-35] and models enhance intrateam communication and planning,[21,23-25,28,36] and reduced fluoroscopy time.[19,20] In one retrospective study of 126 adolescent idiopathic scoliosis patients with a Lenke 1 deformity, Yang et al[1] showed that 3DP models used for surgical planning resulted in reduced operative duration and blood loss. However, there was no effect on the rates of screw placement accuracy, complications, and hospital length of stay.[1] Another study surveyed spine surgeons and found that anatomical details were better visualized on a 3D spine model compared with CT or MRI 3D reconstructions. They reported a 22% reduction in operation duration, which the authors attributed to enhanced anatomical visualization and more detailed preoperative planning which resulted in easier and more accurate implant and screw positioning, less frequent reference to conventional imaging, and increased implant efficiency and reduced cost of surgery.[18] In addition, they reported improved intra-surgical team communication and between surgeons and patients.

3DP technology has also been used for physician training and patient education applications. It provides a physical and tactile anatomical model that serves as an aid in understanding the spine anatomy of each patient and the planned surgical intervention. 3DP models enhance patient understanding of their condition and the surgical plan, which has been shown to increase rates of patient informed consent by as much as 25%.[37] In postoperative patient questionnaires, many patients reported that patient-specific 3D printed spinal models improved anatomical understanding of their condition as well as comprehension of their planned surgical procedure and its associated risks.[18,25,38] 3DP spine models may also be able to replace or supplement cadaveric models in resident training and education, as they offer customizability and greater availability, and have none of the health and safety issues associated with cadaveric models.[39] 3DP has been shown to be beneficial in improving training in spine surgery, including complex procedures such as open door laminoplasties and needle placement for image-guided spinal procedures.[27,40,41] Li et al[26] showed that training using a 3DP spine model helps increase skills and confidence of surgical trainees.

Radiation exposure from intraoperative fluoroscopy and CT imaging used in navigation systems remains a concern to patients and surgeons as an increase in tumor incidence has been reported in each of these groups in sufficient radiation doses.[42-44] The use of 3DP spine models in presurgical planning may potentially reduce intraoperative radiation exposure. However, a preoperative CT scan is typically required. Our review identified 2 studies that measured intraoperative radiation exposure from fluoroscopy in adult deformity cases with 3DP technology and without 3DP.[19,20] Although there was a nonsignificant reduction in fluoroscopy exposure by 61.2% in the 3DP cases compared with the non-3DP cases, more studies are needed to elucidate stronger evidence of radiation dose reduction in cases when 3DP is used.

Pedicle screw placement accuracy remains a major concern for spine surgeons, and misplacement has been reported to occur in up to 20% to 30% of cases.[45,46] Free-hand implantation of screws depends heavily on surgeon skill and the

Table 3. Summary of 3-Dimensional Printing (3DP) Training, Education, and Team Communication Studies.

Study	3DP intervention	Patient satisfaction/ understanding	Team communication	Surgical education	Reduced operating time	Conclusions/findings
D'Urso et al, 2005	3DP spine model	Improved	Improved	—	Y	Patients stated that the biomodels improved informed consent and communication, and responded favorably to the biomodel when it was used to explain the pathology and operative plan, which allowed them to achieve a far greater understanding of their problem, the surgical plan, and associated risks.
Coote et al, 2019	3DP spine model	Improved	Improved	—	Y	Enhance visualization of patient anatomy, allowing patients and their families who lack medical training to interpret and understand cross-sectional anatomy, which in our experience, enhanced the consultations.
Guarino et al, 2007	3DP spine model	Improved	Improved	Improved	Y	Surgeons found 3DP models useful for preoperative planning, reference during surgery, communication with patients, and for increasing the safety of the procedure.
Yang et al, 2011	3DP spine model	Improved	Improved	Improved	—	Helpful as a communication tool, providing patients with a better appreciation of their condition, details of the planned surgical procedure and the subsequent risks involved while facilitating communication within the surgical team. Surgeons appreciated the "hands-on" aspect provided by the models.
Mao et al, 2010	3DP spine model	—	Improved	—	—	Allowed 3D observation and measurement of the deformities directly, which helped the surgeon to perform morphological assessment and communicate with the patient and colleagues.
Li et al, 2018	3DP spine model	—	—	Improved	—	3D printed lumbosacral spine phantom with realistic spondylosis can be made to facilitate novice training in minimally invasive spine procedures, although at a high cost ($5400) and setup time (1 month).
West et al, 2014	3DP spine model	—	—	Improved	—	3DP ultrasound phantoms that are derived directly from patient anatomy have strong potential as learning tools and preprocedural planning tools in cases involving pathologies, implants, or abnormal anatomies.

Table 4. Summary of 3-Dimensional Printing (3DP) Production Type, Materials, Costs, and Time.

Study, author (year)	3DP type	Material(s)	Average cost estimate (USD)	Average time estimate (hours)
Izatt et al (2007)	SLA	Polymer	1200.00	14
Wang YT et al (2016)	SLS	Polymer	361.50	18
Pijpker et al (2018)	SLA	Polyamide	175.00	24
Coote et al (2019)	SLA	Photoreactive resin	447.50	72
Guarino et al (2007)	SLA, FDM	Polymer	1550.00	
Mao et al (2010)	SLA	Polystyrene	289.00	10.5
Li et al (2018)	SLA	Calcium sulfate hemihydrate	5400.00	720
West et al (2014)	SLA	Resin	677.71	24
Liu et al (2017)	SLA	Resin	290.00	36
Pan et al (2018)	SLA	Polycarbonate	—	72
Cecchinato et al (2019)	SLS/MySpine	Unspecified	—	840
Takemoto et al (2016)	SLM	Titanium	1000.00	24
Garg et al (2019)	FDM	Unspecified	—	11
Putzier et al (2017)	SLS/MySpine	Polyamide	—	168
Sugawara et al (2013)	SLA	acrylate	250.00	60
Wang D et al (2016)	SLM	ABS, stainless steel	—	—
Mokawen et al (2019)	SLM	Titanium, SiCaP	—	—
Marengo et al (2019)	SLS	Polyamide	—	—
		Simple average	1058.25	149.54

Abbreviations: SLA, stereolithography; SLS, selective laser sintering; SLS/MySpine, MySpine 3DP guide produced using SLS technology; SLM, selective laser melting; FDM, fused deposition modeling; ABS, acrylonitrile butadiene styrene; SiCaP, Silicate-substituted calcium phosphate.

occasional utilization of intraoperative fluoroscopy to confirm positioning. However, 3DP screw drill guides and navigational templates, which are customizable and made to be anatomically accurate based on pre-operative imaging, may offer more accurate and safer screw placement during deformity-correcting spine surgery.[47] Some studies in our review have shown that the use of 3DP pedicle screw templates may result in improved screw placement accuracy and precision, reduced operative time, and reduced perioperative complications and radiation exposure, compared to non-3DP (fluoroscopy or CT) guided procedures.[32,48-50] Our review shows that the use of 3DP may result in favorable deformity correction outcomes, with an average correction rate of 72.5% and a high screw placement average accuracy of 96.5%. It is worth noting, however, that there exists variation in operating time among spine surgeons, which depends on skill level and prior training with screw implantation. Advanced free hand surgeons may not benefit as much from using screw drill guides in their practice as a general spine surgeon would.

Finally, production costs of 3DP surgical planning models vary widely in the reviewed studies, with marginal costs ranging from $175 for a 3DP template model to $5400 for sophisticated 3DP spinal phantom training models. Production lead times also varied widely from 9 hours to 1 month within the reviewed studies. Similar to 3DP in surgical planning, there is a wide range of per-unit manufacturing costs and production time across various types of materials and printers in the application of 3DP in creating screw guides. Costs ranged from $175 to $290 in marginal costs, although reporting was limited among the reviewed articles, and there was no discussion regarding costs and production times. There was also a wide variability in 3D printing materials in the reviewed studies, which included resin, polystyrene, polymer, polyvinyl chloride, polycarbonate, polylactic acid, titanium, stainless steel, polyamide, and acrylate. Few studies discussed comparisons between materials, especially metal. Takemoto et al[48] reported a very high pedicle screw accuracy rate (98.4%) when using 3DP titanium screw templates. Although titanium is 5 times more expensive than plastic polyamide, which is one of the most commonly used material in 3DP, the authors emphasized the superior strength and durability of titanium metal compared with polyamide plastic, which ensures greater accuracy, reduces the risk of warping, flexing, and potential damage to the guide during intraoperative manipulation.[48] The authors also noted that plastic is more likely to produce intraoperative debris when in contact with drills and other surgical tools, posing a potential risk to the safety of nearby neurovascular structures, and which may lead to retained micro-debris. Another study by Wang et al[28] showed that 3DP screw templates made with stainless steel have better screw placement accuracy, are easier to autoclave, and are less prone to perioperative damage and deformation, compared with 3DP resin templates. It is important to note that the reported variation in production costs of polymer-based 3DP models, which can range up to $2500, pales in comparison with the relatively lower costs of other materials that have demonstrated comparable efficacy.

There are still limitations associated with the use of 3DP screw guides and templates. There were 4 studies that disclosed conflict of interest, including 3 studies with authors receiving consulting fees from device manufacturers (Medacta and Medtronic),[20,29,35] and 1 study which was supported by DePuy

Acromed, Inc and Medtronic Sofamor Danek.[22] Although various studies have shown reduced operative times when using 3DP screw guides, it is important to also consider the production time which can take several hours and involves collecting and processing imaging data and designing and printing the 3D screw guides. Production costs of 3DP surgical planning models vary widely in the reviewed studies, likely due to lack of standardized manufacturing processes. In addition, a common problem reported in studies involves clean bone preparation, which requires complete removal of soft tissue for optimal template fixation. This is a time-intensive process that has been associated with increased intraoperative blood loss.[4,50,51] Additional time and costs associated with implementing the technology in hospitals and training staff on how to use the technology must also be considered. Future directions in 3DP technology must focus on creating a user-friendly and commercially viable 3DP system that allows for standardization and streamlining of the production process into a more cost-effective and efficient model.

Conclusions

Three-dimensional printing is currently used for presurgical planning, patient and trainee communication and education, pre- and intraoperative guides, and screw drill guides in the treatment of scoliosis and other adult spinal deformities. Studies evaluating the use of 3DP drill guide templates have shown significantly better screw placement accuracy compared to the non-3DP cohort, and favorable deformity correction rates. Utilization of 3DP technology in the treatment of adult spinal deformities has been shown to significantly reduce operative duration, compared to the non-3DP cohorts. However, there are no significant difference in perioperative blood loss between the 3DP and non-3DP cohorts among the reviewed articles. Analysis of 3DP technology types, materials, and manufacturing costs and times yielded variable results. Stereolithography remains the most commonly used 3DP method.

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