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Role of Three-Dimensional Printing (3DP) in Spinal Deformity Correction

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ABSTRACT

Three-dimensional printing (3DP) has emerged as a transformative technology in modern medicine, enabling the conversion of radiological imaging data into precise, patient-specific anatomical models. In spine surgery, 3DP has gained significant attention due to its ability to enhance preoperative planning, improve surgical accuracy, and facilitate the development of customized implants and instrumentation. With continuous advancements in printing techniques and biomaterials, 3DP is increasingly integrated into the management of complex spinal pathologies, including deformities, trauma, malignancies, and degenerative conditions...

KEYWORDS: Three-dimensional printing; Spine surgery; Pedicle screw; Surgical planning; Patient-specific instrumentation; Spinal deformity ys**.**

INTRODUCTION

Three-dimensional printing (3DP) serves as a transformative technique that converts digital images into tangible, functional objects. Broadly, 3D printers operate through either additive or subtractive methods—constructing objects by adding material layer-by-layer or by selectively removing layers, respectively. Notably, recent years have witnessed substantial advancements in 3DP, driving its integration into diverse aspects of daily life (1).

The concurrent reductions in the physical footprint, error rates, and costs of 3D printers, coupled with enhanced accessibility to 3D imaging platforms, have facilitated the widespread adoption of this technology, particularly in medical research. Moreover, the exploration and development of novel printing materials (inks) have played a pivotal role in translating 3DP technology into clinical applications (2).

3D printing technology

Several studies have detailed the different forms of 3D printing available for medical applications. Three key methods of 3D printing for medical applications include (3):

In patients with spinal problems, 3D printing has been employed in multiple facets of patient treatment. These encompass pre-operative uses, including patient education, enhanced imaging assessment, and the formulation of surgical plans. Intra-operative assistance is facilitated through the fabrication of patient-specific jigs and implants. Customized jigs serve as guides, facilitating the precise placement of pedicle screws and cages, particularly in patients with intricate anatomical structures, such as those with severe spinal abnormalities. 3DP has created new opportunities in the management of patients with significant spinal involvement, such as in cases of malignancies and infections (4).

1. **Fused deposition modeling (FDM):** the deposition of a thermoplastic polymer using an extrusion process. This is the most cost-effective approach, however it is not suitable for intraoperative usage because it can only be performed on materials with a low melting temperature, making sterilizing problematic (**3**).
2. **Selective laser sintering (SLS)/Electron beam melting (EBM):** use a laser or electron beam energy source to work on a powder-based material. This powder can contain a variety of materials such as titanium, nylon, ceramics, and

stainless steel. This technology offers exceptional accuracy and can print objects as small as 0.5 ± 0.2 mm. The disadvantage of this technology is that substantial processing is required after printing to provide a smooth surface if a laser is employed (**5**)

3. **Stereolithography (SLA):** is based on photocurable liquid resin curing. It entails the serial solidification of layers of liquid on top of one another as the 3D object expands to its final shape. This results in material with a good finish, although the resin is relatively pricey (**6**)

In all of these techniques, CT or MRI scans are used to obtain DICOM (DICOM® - Digital Imaging and Communications in Medicine - is the international standard for medical images and related information) pictures of the proposed site. This is followed by the construction of a computer-based 3D CAD model (.stl file) of the vertebral column, which can then be used to generate additional jig and implant models. (**Fig. 1**). The model is then printed by fusing or depositing materials such as metals, polymers, powders, ceramics, liquids, or living cells in consecutive 2D layers. The most basic 3D models are printed straight from this CAD file, allowing to better comprehend the anatomy of a complex spinal deformity or determine the extent of a cancer (**Fig. 2**).(**7**)

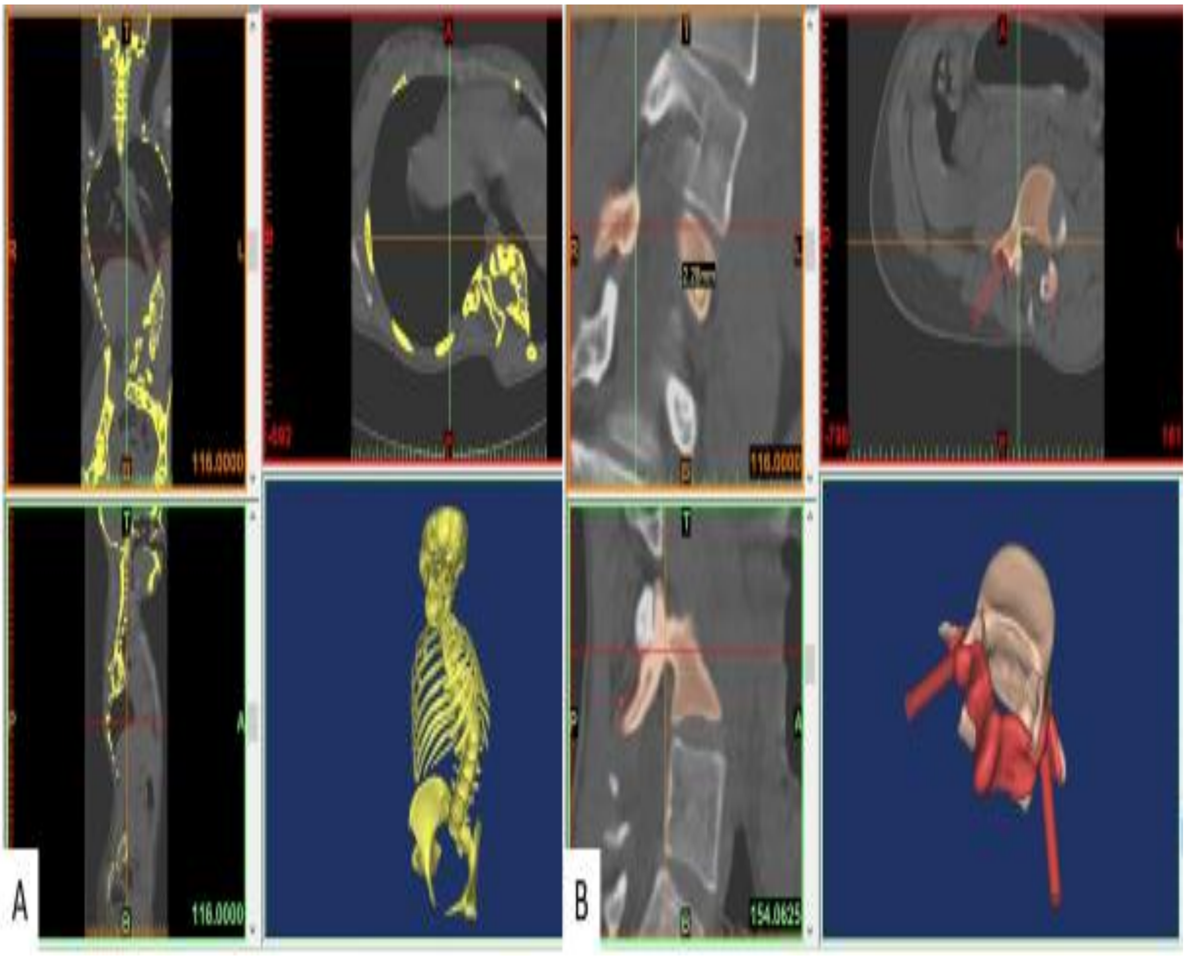

Figure 1: 1A) pre-operative creation of a 3D CAD model of the spine of a scoliosis patient.1B) Creation of best pathway for pedicle screw placement in the software which helps in development of drill guide (7).

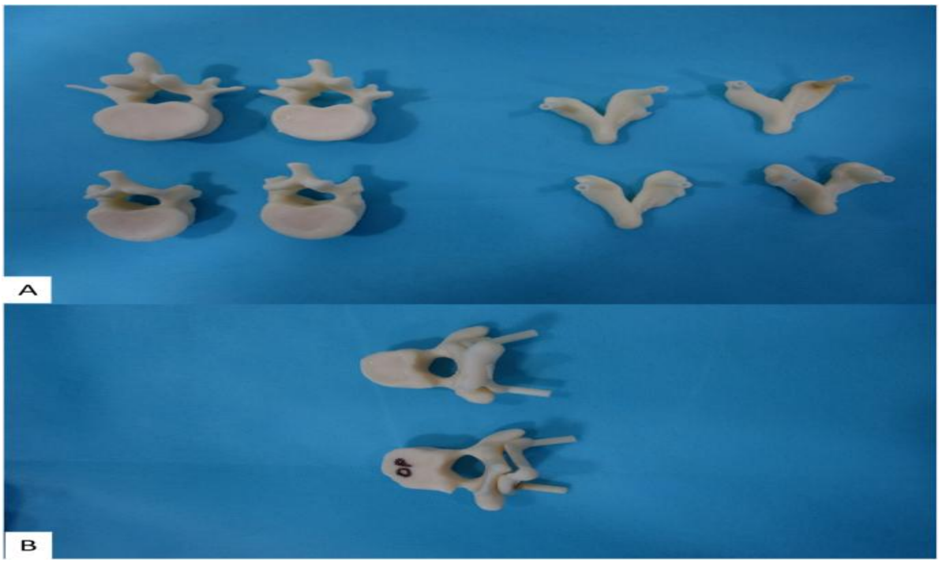

Figure 2: 2A) 3D printed individual vertebrae of various thoracic levels along with drill guides .2B) 3D printed drill guide being assessed ex-vivo prior to surgery (7).

Extensive study has been conducted to determine the best materials to use to construct these 3D models, which best approximate the densities of human vertebrae and hence provide the finest haptic sensation. Hao et al. found that a combination of 15% gypsum combined with 100% clear resin and 10% castable resin mixed with 90% clear resin had the optimum internal structure for forming a vertebra (**8**).

According to Clifton et al.'s feasibility research, a dual material print consisting of polylactic acid [PLA] and polyvinyl alcohol [PVA] simulates the sensation of in vivo instrumentation during pedicle probing, tapping, and screw installation (**9**)

For difficult cases, intraoperative model preparations to guide instrumentation have been described. This entail creating a 3D model that templates over the 3D scan of the vertebra, using cues from precise haptic spots. The guides can be inserted in a comparable orientation intraoperatively and have been demonstrated to produce better results than free hand screw placement in the cervical, thoracic, and lumbar spine. They have also been employed in more complicated instances, such as deformity patients or compression screws in spondylolysis (**10**).

A more recent trend is the use of patient-specific implants, such as interbody fusion cages, 3D printed vertebral bodies in cancer patients, and, most recently, implantable intervertebral discs. The focus has now switched to the use of more biological material coated surrounding implants, which can reduce failures, particularly pseudarthrosis and subsidence (**11**). There has also been the creation of drug-eluting polymers and nanocomposites to aid in bone regeneration (**12**).

As the use of these devices grows, it is critical to define and adhere to rules for the materials that will be used intraoperatively. Various organizations, including the FDA, have recently established guidelines, with a primary focus on quality control procedures that must be considered at every stage of 3D implant production (**12**).

Applications in spine care

D'Urso et al. published one of the first articles describing the use of 3DP in the spine, using a biomodel to help plan and understand cases more effectively (**13**). Following this, for the following 15 years, these biomodels were the only primary use of 3DP in spine care. Only until 2015 did the entire potential of 3DP in spine care become apparent, with the development of models for resident and patient education, intraoperative helping guides, and patient specific implants. Currently, 3DP is present in practically all major spinal pathologies to varying degrees, including spine trauma, degenerative pathologies, malignancies, and complicated kyphotic and scoliotic deformities. It has also played a role in minimally invasive spinal surgery. 3DP has resulted in improved understanding, investigation, and care of all spinal diseases. (**7**)

Pre-operative planning

Pre-operative planning in the form of simulations on radiation-free biomodels is a useful tool, particularly in situations with complex anatomy or when revision treatments are planned (**14**)

The models are X-Ray imaging compatible, allowing for easy study of screw location sizes and geometries. Authors have changed to models that feature translucent and colored elements to aid in better identifying the size and boundaries of sick tissue, such as bone tumors. Models that may be disassembled to simulate surgical resection of pathology and then recreated are now available. Pre-operative planning using biomodels reduces operating time (**7**).

They lower the risk of surgery by minimizing the possibility of encountering unanticipated anatomy or relative location of structures and/or equipment. Parr et al. shown that reducing operative time by 14 minutes could potentially save costs for health care providers (**15**)

Öztürk et al. conducted a Level I investigation on AO type-C thoracolumbar fractures for posterior long-segment fixation, highlighting the benefits of shorter surgical times, lower blood loss, and radiation exposure (**16**). In another case report, Liawrungrueang et al. used a 3D model to help with pre operative planning in a rare case of bilateral pure facet joint dislocation in the thoracolumbar junction (T11-T12) without facet fracture, allowing for emergency early open reduction and instrumentation with fusion (**17**).

Galvez et al. discovered a shift in surgical technique in some patients as a result of preoperative planning. This resulted in fewer surgeries and less aggressive surgical procedures **(18)**, pre-operative examination of 3D models in deformity procedures has improved outcomes, with surgeons gaining confidence in doing higher grade osteotomies while keeping safety in mind (**19**).

Patient specific instrumentation

Patient specific instrumentation is being utilized in a range of pathologies of the spine including infection, degenerative diseases, malignancies and deformities. It is also being utilized at all levels from cervical spine to sacrum and helps orthopaedic surgeons combat complex problems by providing tools and implants which fulfil functions that 'off-the-shelf' implants would not be able to (**20**).

Interbody cage

Over the last 50 years, spinal implants have evolved in response to advances in biomechanics and bone biology. studies demonstrated how 3DP has enabled markets to create customized interbody cages with features such as bone growth windows, surface porosity, endplate matching, body lattice, and microporous endplates, which allow for integral fixation and reduce stress shielding, thereby preventing subsidence and pseudoarthrosis (**21**).

Vertebral body substitutes

A substantial quantity of case reports and case series exists regarding custom-made implants for the stabilization of the anterior column of the spine following the resection of significant malignancies or subsequent to infectious spondylodiskitis. These investigations have demonstrated a novel approach created to address these disorders throughout the spinal cord, from the cervical spine to the sacrum, which often have a dismal prognosis (**22**).

Pedicle screw guides

Despite being the workhorse of modern spinal instrumentation, pedicle screws have been linked to problems caused by screw malpositioning and pedicle perforation. Instrumentation of the paediatric cervical and thoracic spine, cannulation of sclerotic or dysmorphic pedicles, and neurofibromatosis with concomitant spinal deformity are examples of conditions where pedicle screw malpositioning may occur more frequently. To simplify the screw application process, 3D printed patient-specific guides have been developed to assist in drilling the appropriate path (**7**)

Li et al. discovered that 3D printed navigation templates enabled a safer, more effective, and accurate screw placement than free hand surgery in odontoid fractures (**23**). A Level 1 systematic analysis of 13 research including 330 patients found that the 3D-printed navigation template increases the precision of pedicle screw insertion in cervical spine procedures, hence improving outcomes (**24**)

In addition to 3D printed patient-specific drill guides, there has been recent development of screw guides in the form of modular devices or cannulated screws. Pijpker et al. performed a cadaveric study to compare the two procedures. They discovered that the accuracy of the 3D printed drilling guides is very high, eliminating the requirement for cannulated screws or modular guides for both the technically challenging extrapedicular screw procedure and intrapedicular screw insertion (**10**)

Mobbs et al. demonstrated that drill guides can also be employed in small corridors to implant compression screws across a pars defect in spondylolysis patients (**25**)

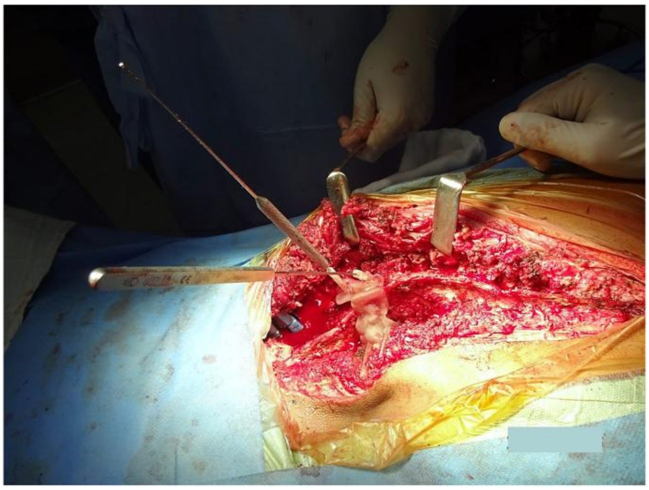

Figure 3: Intraoperative photograph of 3D printed drill guide in use (7).

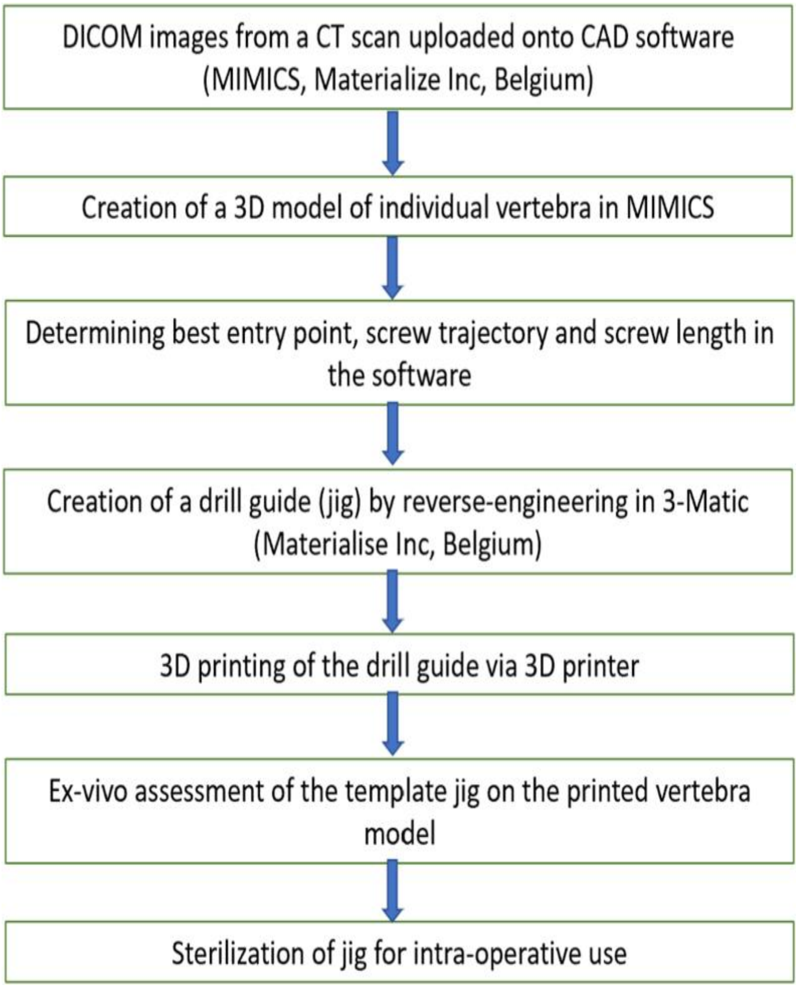

Figure 4: Workflow diagram as a guide for creating drill guides (7).

Deformity correction

Adolescent idiopathic scoliosis is associated with various physical and mental health issues. Its management involves bracing in lesser degrees of curve and operative intervention for larger curves. Custom bracing using 3DP has been in use since 2015, though results are sketchy. Newer modifications in this field include patient specific custom braces which are also capable of detecting the pressures it applies on the human body, allowing fine-tuning of the brace and making the process of treatment more comfortable without compromising on the effectiveness of the brace (**26**).

Minimally invasive surgeries

Minimally invasive surgery is one of the most recent developments in spine surgery, where 3DP has played an important role. Thayaparan et al. developed a patient-specific kit for performing minimally invasive transforaminal lumbar interbody fusions (MI-TLIF). They demonstrated placement accuracy of 97.8% on postoperative CT scans, with few problems in the 639 pedicle screws implanted using 3D manufactured jigs (**27**).

Ling et al. used 3D printed implants to perform a multilayer oblique lumbar interbody fusion (OLIF) with good results (**28**). Yang et al. used 3DP in endoscopic discectomy procedures, and using patient-specific implants allowed for greater access without destroying superfluous bone due to the availability of an additional portal (**29**)

The Role of 3D-Printing for Pedicle Screws Placement in Spinal Deformity Correction

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 (**30**).

Three-dimensional printing technology involves using computed tomography (CT) or magnetic resonance imaging (MRI) 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. 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 (**31**).

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. 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 (**32**).

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 (**33**).

Compared with conventional imaging (eg, intraoperative fluoroscopy), 3DP screw placement guides provide improved screw placement accuracy rates, and models enhance intrateam communication and planning, and reduced fluoroscopy time (**34**).

In one retrospective study of 126 adolescent idiopathic scoliosis patients with a Lenke 1 deformity, Yang et al1 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. 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 (**35**).

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% (**36**).

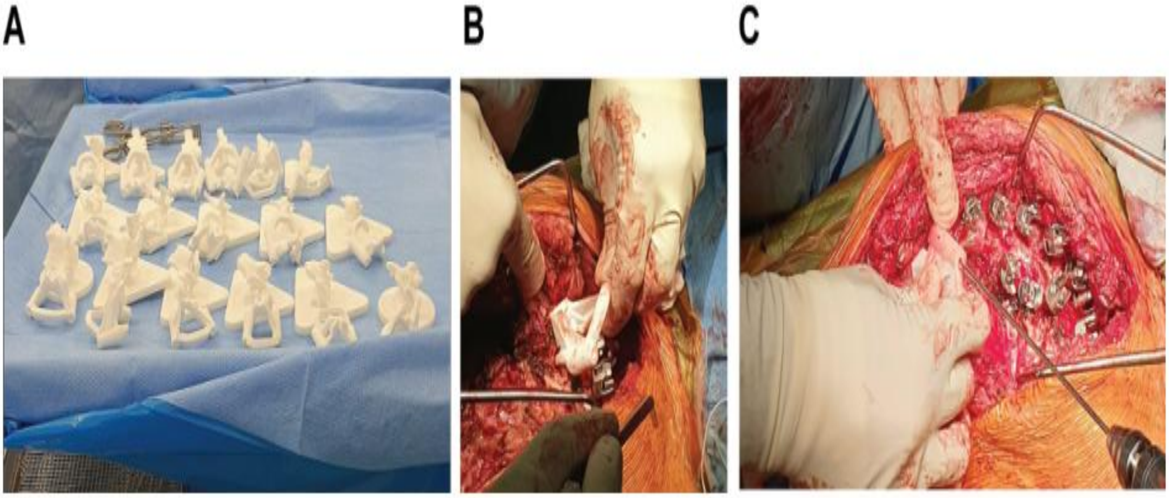

Figure 5: sample images of custom 3D printed pedicle screw guides. Figure A shows sterile, back table preparation of all 3D printed guides for a specific patient, B shows one specific guide being placed at planned instrumented level, C shows a pedicle tract being drilled with orientation provided by the custom 3D printed guide (36).

Figure 6: 3-Dimensional printed model of complex kyphoscoliosis (36).

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