Journal of Clinical Orthopaedics and Trauma xxx (2018) 1–8

Contents lists available at ScienceDirect

Journal of Clinical Orthopaedics and Trauma

journal homepage: www.elsevier.com/locate/jcot

Current status of 3D printing in spine surgery

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ARTICLE INFO

Article history:
Received 15 May 2018
Accepted 2 August 2018
Available online xxx

Keywords:
Additive manufacturing
Patient-specific implants
Rapid prototyping
Spine surgery
Three-dimensional printing

ABSTRACT

Three-dimensional printing (3DP) is one of the latest tools in the armamentarium of the modern spine surgeon. The yearning to be more precise and reliable whilst operating on the spine has led to an interest in this technology which has claimed to achieve these goals. 3D printing has been used pre-operatively for surgical planning and for resident or patient education. It has also found its way to the operation theatre where it is used to fabricate customized surgical tools or patient-specific implants. Several authors have highlighted significant benefits when 3D printing is used for specific indications in spine surgery. Novel applications of this technology in spine surgery have also been described and though still in a nascent stage, these are important for this technology to sustain itself in the future. However, major limitations have also come to light with this technology in use. This article seeks to review the current status and applications of 3D printing in spinal surgery and its major drawbacks while briefly describing the essentials of the technology. It is imperative that the modern spine surgeon knows about this important innovation and when and how it can be applied to improve surgical outcomes.

1. Introduction

Surgical practice has evolved over the last few decades to become less invasive, more precise and safer without compromising on the surgical time. From the use of minimally invasive techniques to the use of navigation, from the development of safer approaches to the use of hi-tech simulators in surgical training – new innovations have continuously enhanced and empowered the modern surgeon. The past few years have seen tremendous advances in medical imaging and bioengineering, which together have fathered a new child in the form of three dimensional printing (3DP) – the latest innovation in modern surgical practice. The dramatic evolution of medical imaging has seen it become less invasive and more informative at the same time. High-resolution three-dimensional image data can be acquired in a very short time. This data can be processed by various softwares to enable three-dimensional visualization and multi-planar reformation, which serve as a template for its eventual use in 3DP.

Arguably, the sectors most influenced by the advent of 3DP technology have been cranial and spine surgery. Apart from dealing with degenerative spine conditions, spine surgeons need to engage in complex surgical procedures to treat various congenital and idiopathic spinal deformities. The anatomy of the spine and its close relation to vital neurovascular structures makes it unique and poses inherent surgical challenges when dealing with complex deformities or spinal tumours. Any technique which aids in surgical planning and improves the procedural accuracy in such situations would certainly be welcome.

3DP is essentially a manufacturing method in which objects are made by fusing or depositing materials—such as metal, plastic, powders, ceramics, liquids, or even living cells—in layers to create a 3D object. This process has also been referred to as rapid prototyping (RP), additive manufacturing (AM) or solid free-form technology (SFF).[1] The purpose of this review is to familiarize the reader with the technology of 3DP, discuss its varied applications in spine surgery, outline its limitations and shed light on the future directions of this technology in spine surgery.

2. Three dimensional printing: a brief background

Charles Hull is credited with the first use of the 3DP technology (which he called 'stereolithography') in the early 1980s.[2] Hull, who possesses a bachelor's degree in engineering physics, later went on to establish the company 3D Systems which developed the world's first 3D printer calling it a 'stereolithography apparatus'.[1] Inspite of technological advances since then, the essential principles of 3DP

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https://doi.org/10.1016/j.jcot.2018.08.006
0976-5662/© 2018

have largely remained the same. In the early stage of design, a digital 3D model is 'sliced' into two-dimensional (2D) sections akin to the axial sections of computerized tomography (CT) or magnetic resonance imaging (MRI) data. Each 'slice' is then physically recreated by a 3D printer, with a chosen material being laid down layer by layer – culminating into a single solid model, once enough of these 'slices' have been created and fused together. There are three commonly used methods of adding the material in layers[3]:

i) *Fused deposition modelling (FDM)* is where layers are made by depositing a heat-softened polymer by a computer controlled extrusion nozzle. Most economical consumer printers use this technique.
ii) *Selective laser sintering (SLS)* involves a focussed energy source (such as an electron beam or a laser) acting upon a fine powder bed of varied materials which may include nylon, titanium and stainless steel. The shape of a 2D slice is traced out, and the geometry of each layer is created. Simultaneous melting and fusing of these areas is then done.
iii) *Stereolithography (SLA)* uses a light curable resin, on which an optical light energy source works. Chosen areas on the surface of the liquid are solidified. Gradual descent of the floor of the fluid container increases the depth of material. Successive layers of resin are cured on top of each other as the model grows and achieves its final form.

While FDM 3D printers are fast and economical, SLS and SLA printers are the benchmark in medical applications of 3DP technology.[4] In addition to being more accurate, they also allow the use of materials which can withstand common sterilization procedures used prior to surgery whereas FDM printers typically use materials with a low melting point. However, on the downside, they require significant training and technical knowledge prior to use.

3. Applications in spine surgery

In a recent systematic literature review, the three largest medical literature databases were screened for case series in English language describing the use of 3DP in surgical applications. A substantial 7.46% of the total papers on the use of 3DP for any surgical domain were dedicated to its applications in spine surgery.[5] D'Urso et al. were the first to describe the use of 3DP in spine surgery in their paper on spinal biomodelling in 1999.[6] Currently, the application of 3DP in spine surgery can be broadly categorized into three areas: i) use of 3D printed anatomical models for training or pre-operative surgical planning ii) creation of patient-specific surgical instruments such as pedicle screw drill-guides or jigs and iii) printing of customized implants tailor-made to the surgeon's needs. It is interesting that while most papers in the earlier half of the previous decade elaborated the use of 3DP for creating models for pre-operative surgical planning – in the last 5 years, these have given way to case reports and publications involving the use of 3D printed instruments or implants. This change from a more simple and straightforward application to a more nuanced and technically specific application is suggestive of how 3DP technology has progressed by leaps and bounds. We briefly outline the use of 3DP in each of the three areas of focus enlisted above.

3.1. Pre-operative planning using anatomical models

Spine surgeons dealing with scoliosis are familiar with many of the inherent problems of these complex deformities encountered intra-operatively. Vertebral rotation, absent or dysmorphic pedicles and segmentation anomalies are all components of scoliotic spines and distort the anatomical landmarks for pedicle insertion. Current imaging modalities like CT scans or MRI have often been found to be inadequate. 3D printed anatomical models provide the 'fourth' dimension of tactile feedback to the surgeons which can help them anticipate the technical challenges that may be encountered intra-operatively. Almost as a testament to the popular adage – 'the more you sweat in practice, the less you bleed in war' - surgeons can practically carry out the entire surgical procedure and make a note of the technical challenges and the improvisations needed, before the actual surgery takes place.

Various authors have published their experience with these anatomical models for complex spine surgery. Izatt et al.[7] used a detailed biomodel utility survey and discovered from the surgeons' feedback that there was better visualization of anatomical details on the biomodel as compared to other imaging modalities in 65% of cases which were a mix of spinal deformity and tumour patients. Mizutani et al.[8] also reported positively in their experience with full-scale 3D models of rheumatoid cervical spines. Mao et al.[9] used computer-designed polystyrene models in 16 cases of complex severe spinal deformity and claimed to have more accurate morphological information from the models. In another retrospective study, the authors reported that the use of 3D printed models for surgical planning in thoracic scoliosis surgery resulted in shorter operative times and lesser blood loss, but had no effect on the complication rate, the screw misplacement rate or the length of hospital stay.[10] These findings were echoed by Li et al.[11] in a study, wherein they assessed the effectiveness of 3-D printing technology in revision lumbar discectomy cases. Xiao[12] and Kim,[13] in separate papers, have also highlighted the application of 3DP in assisting surgical resection of bone tumours. More recently, the use of 3DP has also been reported in the field of minimally invasive spine surgery (MISS) although there are limitations to its widespread implementation.[14] Zhao et al. have reported on the use of 3D biomodelling-assisted MISS to deal with 13 cases of thoracic ossification of ligamentum flavum. Biomodels of the patients' spinal anatomy were used to determine the angle of insertion of the percutaneous tubular retractors, and also to guide the surgeon towards the location and size of the bony spaces.[15]

Another useful application of 3D printed anatomical models is in resident training and patient education.[16] A tangible and concrete representation of the pathoanatomy can act as a valuable aid in explaining the patient regarding his/her condition and what the proposed surgical procedure intends to achieve. As much as 25% higher patient informed consent scores were obtained when a biomodel was used in comparison to pre-operative image demonstration to explain and educate the patient regarding the nature of the condition and the treatment offered.[17] 3D printed models can be used in lieu of cadavers for training and education of residents. Such models are free of several concerns surrounding cadavers which include lack of availability, health and safety issues and other medicolegal or ethical hassles. These models can also be easily customized to better simulate surgical challenges such as those seen with complex spinal deformities.[18]

3.2. Surgical tools and guides

Pedicle screws are universally the most frequently used fixation technique in spinal surgery. The close proximity of neural structures makes pedicle screw insertion a dangerous proposition though in the hands of most experienced surgeons, the rate of neurological complications is extremely low. However, inserting pedicle screws in the cervical spine or in a scoliotic deformity, particularly in paediatric patients, is certainly more challenging and prone to pedicle wall breeches/perforations. Most surgeons still use a fluoroscopy-guided free-hand technique – however, this

Please cite this article in press as: Garg B, Mehta N, Current status of 3D printing in spine surgery, Journal of Clinical Orthopaedics and Trauma (2018), https://doi.org/10.1016/j.jcot.2018.08.006