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Critical analysis for a safe design of 3D printed Patient-Specific Surgical Guides (PSSG) for pedicle screw insertion in spinal deformities

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ABSTRACT

Pedicle screws are used in spinal fusion for the stabilisation of the spine through a posterior approach. In spinal deformities, such as scoliosis, pedicle screw placement is especially challenging due to vertebral rotation and landmark distortion. Conventional surgical procedures such as Free-hand screw insertion mainly rely on surgeon experience and anatomical landmarks. Image- and robot-guided pedicle screw insertion can improve placement accuracy but require exposure to ionising radiation. Studies of 3D-printed patient-specific surgical guides (PSSG) have shown similar accuracy rates and reduced intra-operative radiation. Nevertheless, the guide design and workflow of these devices present significant challenges.

This manuscript presents a narrative review of the literature regarding the analysis of designs, manufacturing, and technical considerations for patient-specific screw guides (PSSG). We focus on the analysis of imaging criteria, design variables (including spinal levels, anatomical landmarks and guiding tools), manufacturing technology, 3D-printing technology and validation studies (*ex vivo* and in vivo). We also discuss the clinical and economic benefits of PSSGs and provide further dialogue on the limitations and requirements for better adoption of this technology in future.

Compared to Free-hand pedicle screw placement, we find that PSSGs show consistently superior placement accuracies and when compared to image and robot-guided technologies, their use requires less radiation exposure, shorter operative times and economic benefits. The guides are of additional use in cases of complex spinal deformities, especially if guided technologies are not available.

Abbreviations

PSSG	Patient-Specific Surgical Guides
MIS	Minimal Invasive Surgery

1. Introduction

Spinal fusion procedures are used to treat a variety of spinal conditions including deformity correction. It is the most common and effective procedure for spinal stabilisation [1–4]. One of the most critical points is the insertion of the screws within the pedicles, especially in scoliosis patients where the anatomy is rotated in multiple axes. Free-hand screw insertion has remained the gold standard even after the appearance of guided technologies [5]. In Free-hand insertion, the surgeon determines the screw trajectory based on anatomical landmarks, medical images and surgical experience. In patients with spinal deformity, identification of anatomical landmarks is challenging and the suboptimal placement of screws can result in neurological deficit through injury to the spinal cord or nerve roots [6-9].

Free-hand pedicle screw insertion has been reported to carry a misplacement rate of between 5 and 40% [10]. In addition, it is highly dependent on the surgeon's experience. Image and robotic guided pedicle screw insertion have a significantly lower screw misplacement rate of between 3 and 11% [11–14] but their cost-effectiveness in spinal surgery is still not clear [15–17]. Furthermore, changes in patient position from the initial CT coordinates registration lead to inaccuracies and mandate additional image acquisition. Despite this, robotic and image-guided technologies are reducing radiation exposure [18], but the clinical benefits are yet to be evaluated in paediatric patients [19,20]. Total radiation burden is a concern in young spinal

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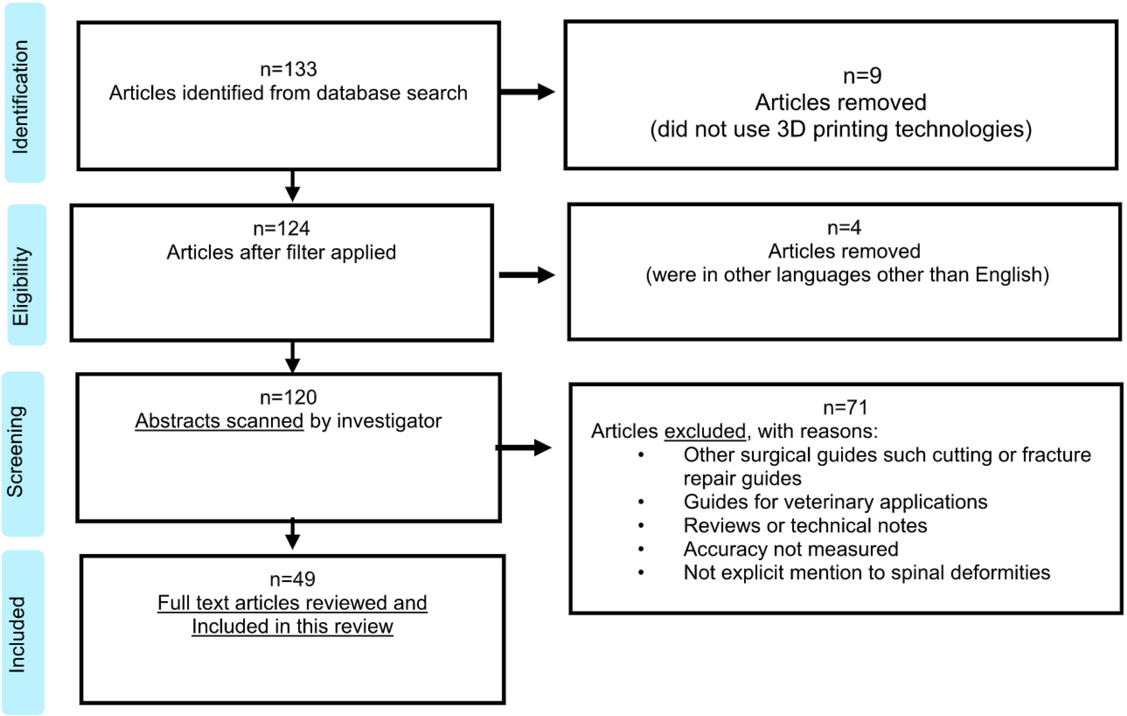


Fig. 1. Diagram flow of the study selection.

deformity patients as continuous radiation exposure will be required during follow up assessments [21–25] and future revision surgeries [6,22,24]. The incidence of secondary malignancies amongst scoliotic patients due to medical imaging radiation exposure is becoming more evident [21,23,26–28]. To overcome the above aforementioned disadvantages of the different pedicle screw insertion techniques, several groups have been developing 3D printed patient-specific surgical guides (PSSG). These studies suggest that PSSGs for pedicle screw insertion offer a potential alternative to the image and Robot guided technologies, by eliminating the need for intra-operative radiation exposure and providing comparable pedicle screw insertion accuracies [29–33].

In this review, we aim to translate the engineering features to clinicians and clinical considerations to engineers. We critically analyse the design and development workflows including detailed analysis of image acquisition, processing criteria, design variables (guiding tools, contact, anatomical landmarks), 3D printing considerations (different technologies, materials and cost) as well as testing and validation *in vitro, in vivo* and the clinical environment. We also consider the clinical and economical benefits of PSSGs based on the available literature and provide further discussion on the limitations and requirements for better adoption of this technology in the future.

2. Methodology

We comprehensively search the Ovid, PubMed, Web of Science databases using a combination of the following keywords: Patient-specific, guide, spine, 3D printing, scoliosis, rapid prototyping, additive manufacturing, templates, jig, pedicle screw, spine deformity and spinal fusion. The review focuses on patient-specific 3D printed drilling guides or templates utilised exclusively for pedicle screw insertion during posterior spinal approaches. The following studies were excluded, those that:

(a) did not use 3D printing technologies;
(b) were in languages other than English or where an English translation could not be found;
(c) focused on other surgical guides such as cutting guides or fracture repair;
(d) developed guides for veterinary applications;
(e) technical notes or publications where accuracy data was not provided;
(f) do not have any explicit link to spinal deformity.

A total of 133 studies were initially identified. A total of 49 publications met the inclusion and were included in this review (as shown in Fig. 1).

Articles were later classified according to 1. Study design (Specimen, level and number of screws). 2. Design factors (CT slice thickness, anatomical landmarks, contact, guiding tools and material and 3D printing technology used) summarised in Table 1A and 4A, 3. Outcomes (cost operative time, intra-surgical radiation, accuracy Guides and Free-Hand) summarised in Table 1B and 4B.

3. Results & discussion

Two types of PSSG for pedicle screw insertion were reported in the literature. The most commonly reported approach in the literature are those for use during open surgery (Table 1A and 1B) whilst a smaller number of studies describe PSSGs for minimally invasive approaches (Table 4A and 4B).

3.1. *Design and manufacturing workflow of a 3D printed patient-specific surgical guide for pedicle screw insertion*

Design manufacturing of patient-specific pedicle screw guides follows a standardise workflow as shown in Fig. 2. This workflow compromises of 6 key steps, which include 1. Image acquisition, 2. Image reconstruction, 3. Pre-surgical planning and 4 Device design, 5. 3D printing manufacturing, 6. Testing & validation. We will look at each of these steps in detail and discuss them in relation to current literature in the following sections (Fig. 2).

Table 1A

Study design and Design factors of Patient-Specific Surgical Guides (PS SG) for Open posterior spinal fusion surgery.C: Cervical, T: Thoracic, L: Lumbar, CTL: Cervical, Thoracic and Lumbar. FFF: Fused Filament Fabrication, SLA: Stereolithography SLS: Selective Laser Sintering. **Anatomical Landmarks (also in Fig 5 below)** – **1:** Upper part of Spinous process. **2:** Sides of Spinous process **3:** TP (Transverse process) **4:** Base of TP **5:** Superior Articular process **6:** Inferior Articular process **7:** Laminae.

Authors and year	Study Specimen	SpineLevel	Number of Specimens	Screws	CT ImagingSlice thickness	Guiding tool	AccuracyGuides (>2 mm)	Contact	Anatomical landmarks	3D Printing TechnologyMaterial
(Goffin et al., 2001)	Cadaveric Clinical	C	52	164	1 mm	Drill	83.33%	Medium Knife-edge	7,2,1	SLA Acrylate resin
(Berry et al., 2005)	Cadaveric	CTL	4	50	2 mm	Drill	56%–100%	Low Knife-edge Multilevel	7,1,3	SLS Polyamide (Duraform)
(Lu et al., 2012)	Clinical	T	16	168	0.625 mm	Drill	93.45%	Full	7,1,3	SLA Acrylate resin
(Ma et al., 2012)	Cadaveric	T	20	240	0.625 mm	Drill	93.4%	Full	7,1,3	SLA Acrylate resin
(Porada, 2012)	Cadaveric	L	2	14	2 mm Interpolation to 0.5 mm	Drill	100%	Low Knife-edge	3,1	SLA Acrylate resin Stainless steel (sleeves)
(Kawaguchi et al., 2012)	Clinical	C	11	44	0.7 mm	K-Wire	95.4%	Full Unilateral	3,7	- Hard plastic (Lexie Co)
(Fang et al., 2012)	Clinical	L	1	4	–	Drill	Deviation 1.05°	Low	7	- Titanium (sleeves)
(Merc et al., 2013)	Clinical	L	20	54	0.5 mm *prone	Drill Temporary fixation	100%	Medium Multilevel	5,1	SLS Polyamide
(Sugawara et al., 2013)	Clinical	T	10	58	0.625 mm	Multistep (3)	Mean deviation 0.87 ± 0.34°	Full	7	SLA Non-soluble acryl
(Kaneyama, 2013)	Clinical	C	3	32	0.75 mm	Multistep (3)	Grade 0 100%	Full Unilateral	7,1	SLA Non-soluble acryl
(Kaneyama et al., 2014)	Clinical	C	23	48	0.75 mm	Multistep (3)	97.9%	Full	7,1	SLA Non-soluble acryl
(Kaneyama et al., 2015)	Clinical	C	20	80	0.75 mm	Multistep (3)	97.5% (grade0)	Full	7,1	SLA Non-soluble acryl
(Lamartina et al., 2015)	Cadaveric	TL	3	43	Low dose	Multistep (2)	91.3%	Low Knife-edge	1,3	–
(Putzier et al., 2017)	Clinical	TL	4	76	Low dose	Multistep (2)	97.4%	Low Knife-edge	T: 1,7,3 L 1,5,3	SLS Polyamide (PA2200)
(Takemoto et al., 2016)	Clinical	T	40	466	1 mm	Probe	98.6%	Low	1,3,4,7.	SLS Titanium
(Otsuki et al., 2016)	Clinical	CL	3	5	1 mm	K-wire	98.7%	Low	5,1, 3	SLS Titanium
(Deng et al., 2016)	Clinical	C	10	48	5 mm	Drill	97.9%	Full	7,1	SLA Photosensitive resin
(Jiang et al., 2016)	Clinical	C	32	128	0.625 mm	Drill Without sleeve	2 screws of 128 deviated 1 mm 96% grade 0	Full	7,1	SLA acrylate resin (Somos 14,120)
(Hu et al., 2016)	Clinical	T	151	582	0.625 mm	Drill Temporary fixation	96.1%	Full	7,1	SLA acrylate resin (Somos 14,120)
(Farshad et al., 2017)	Cadaveric	TL	3	96	0.64 mm	Drill Cannulated	97.9%	Medium	7,1,3	SLS Polyamide (PA2200)
(Azimifar et al., 2017b)	Cadaveric	L	10	20	–	Drill	90%	Medium	5,6	FFF ABS
(Jiang et al., 2017)	Clinical	C	54	100	0.625 mm	Drill Without sleeve	100% Grade 2 (<2 mm)	Full	7,1	SLA Acrylate resin
	Clinical	C	12	48			100%	Full		

(continued on next page)

Table 1A (*Continued*)

Authors and year	Study Specimen	SpineLevel	Number of Specimens	Screws	CT ImagingSlice thickness	Guiding tool	AccuracyGuides (>2 mm)	Contact	Anatomical landmarks	3D Printing TechnologyMaterial
(Sugawara et al., 2017)					0.625 mm	Drill Multistep (3)			7	PolyJet Non-soluble acryl
(Sugawara et al., 2018)	Clinical	CT	103	813	0.625 mm	Multistep (3)	98.5% without cortical violation Grade 0	Full	7	PolyJet Non-soluble acryl/nylon
(Guo et al., 2016)	Cadaveric	C	23	94	0.625 mm	Probe	95.8%–100% Grade 1 (within pedicle)	Full	7,1	FFF
(Guo et al., 2017)	Model	C	19	37	0.5 mm	K-wire	94.6% Type II <1 mm	Full	4,1,3,7	FFF PLA
(Wang et al., 2017)	Cadaveric *children	L	4	20	0.625 mm	Drill	100% Withing the pedicle	Full	7,1	SLA -
(Liu et al., 2017)	Clinical	T	10	48	0.625 mm	Drill Unilateral Multilevel	93.8% Grade 1 < 2 mm	Full Multilevel	7,2	SLA Resin
(Azimifar et al., 2017a)	Model Clinical *children	TL	M 12 P 1	M 110 P 12	0.625 mm *prone	K-wire	93.63% <1 mm	Low Multilevel	7,1,3,4,6	FFF -
(Alpizar-Aguirre et al., 2017)	Clinical *children	TL	5	84	5 mm Interpolation to 0.625 mm	Multistep (2) (hemicylinders)	96.6%	Low Multilevel	7,1	FFF ABS
(Yu et al., 2017)	Cadaveric	C	12	164	0.625 mm	K-wire Cannulated drill	96.3% < 2mm	Full Unilateral	7,2,4	–
(Zhang et al., 2018)	Cadaveric	C	12	158	0.625 mm	K-wire Cannulated drill	98.1% <1.1 mm	Full	7,2	FFF -
(Pan et al., 2018)	Clinical	TL	20	396	0.625 m	Drill	96.7% Grade 1 < 2 mm	Full	7,1,3	–
(Wu et al., 2018)	Clinical	C	9	57	1 mm	Drill	94.7% Grade 0	Medium	7	- ABS P430
(Kim et al., 2018)	Cadaveric	TL	7	80	0.625 mm	Drill	95% Class 2 <4 mm	Full	–	PolyJet acrylate resin (Somos 14,120)
(Chen et al., 2019)	Clinical	TL	10	173	0.625 mm -	Drill	97.1% < 2 mm	Medium	1,7	PolyJet MED610
(Cecchinato et al., 2019)	Clinical	TL	29	540	–	Drill	90.2% Grade 0	Medium Knife-edge	1,7	–
(Naddeo et al., 2019)	Clinical	T	3	16	0.5 mm -	Multistep (2)	87.5% class 1 <2 mm	Low	–	SLA Dental SG
(Garg et al., 2019)	Clinical	CTL	10	120	0.625 mm	Drill	91.2% Grade 1 <2 mm	Full	–	- ABS
(Tu et al., 2019)	Patient	CTL	9	83	–	Drill	93.98%	Full Multievel	–	SLS Titanium
(Nanni et al., 2019)	Model	C	8	16	1 mm	Drill	100%	Medium	–	PolyJet acrylic resin
(Marengo et al., 2019)	Clinical	L	11	44	–	Drill	96% Grade *A* <2mm	Medium Knife-edge	6,7	–
(Matsukawa et al., 2019)	Clinical	L	43	198	0.5 mm	Drill	97.5% Grade A 0–2mm	Medium Knife-edge	6	–
(Shah et al., 2020)	Clinical	CTL	5	91	–	Probe	75% Class 2 <2 mm	Full	1,7	–
(Vissarionov et al., 2020)	Clinical	TL	10	102	–	Drill	96.3% Grade 1<1 mm	Full	7,4	SLA Dental SG

Table 1B
Outcomes of Patient-Specific Surgical Guides (PS SG) for Open posterior spinal fusion surgery. FH: Free-Hand.

Authorsand year	Design and Manufacturing time	Cost	Operative time (minutes)	Intra SurgicalRadiation	AccuracyGuides(>2 mm)	AccuracyFree-Hand
(Goffin et al., 2001)	1 week	$350–400	–	–	83.33%	–
(Berry et al., 2005)	–	–	–	–	56%–100%	–
(Lu et al., 2012)	–	–	1.24 min per screw	–	93.45%	–
(Ma et al., 2012)	1 h (design)	$50 (material, printer rate)	–	–	93.4%	65%
(Porada, 2012)	–	–	–	–	100%	–
(Kawaguchi et al., 2012)	1 week	$150 (template)	Average operation time 11 patients 283 ± 49 min	–	95.4%	–
(Fang et al., 2012)	4h	$50(material and manufacturing)	Reduces at least 30 min	–	Deviation 1.05°	–
(Merc et al., 2013)	–	–	Minutes, SD 143 (113) Guided 176 (90) FH	–	100%	57%
(Sugawara et al., 2013)	–	1 template $8 vertebra model $17	Mean surgery time 254.2 min (range 136–433 min) 58 screws	–	Mean deviation 0.87 ± 0.34°	–
(Kaneyama, 2013)	–	–	–	–	Grade 0 100%	–
(Kaneyama et al., 2014)	–	–	–	–	97.9%	–
(Kaneyama et al., 2015)	–	2 templates and vertebra model$30 (material)	–	–	97.5% (grade0)	–
(Lamartina et al., 2015)	–	–	–	Pre-surgical Low dose	91.3%	–
(Putzier et al., 2017)	–	–	–	Pre-surgical Low dose	97.4%	–
(Takemoto et al., 2016)	2–3 days	$100 (each template of titanium) $20 (each template of polyamide)	–	–	98.6%	–
(Otsuki et al., 2016)	2–3 days	–	Can potentially save time compared to the image-based navigation technique.	–	98.7%	–
(Deng *et al.*, 2016)	-	-	The device can significantly decrease the operation time.	Fluoroscopic time reduced	97.9%	-
(Jiang *et al.*, 2016)	2–3 days	$30	Average operation time 174.3 ± 27.6 min	Average fluoroscopy shots 2.68 ± 0.82	2 screws of 128 deviated 1 mm 96% grade 0	-
(Hu *et al.*, 2016)	-	-	Possibly reducing the surgical time	Fluoroscopic Time Reduced	96.1 %	50–94 %
(Farshad *et al.*, 2017)	-	-	01:14 ± 00:37 min/2screws guided 01:40 ± 00:59 min/2screws FH	Mean fluoroscopy dose was 889 ± 604.6 mGycm2 Mean time 01:14 ± 00:29 min	97.9 %	81.3 %
(Azimifar *et al.*, 2017b)	-	-	Dissecting can increase the surgery time while trajectory decision making time decrease	The average fluoroscopy shots were 2.68 ± 0.82	90%	-
(Jiang et al., 2017)	2 days	-	171.84+−22.46 min Guides 182.76±28.40 min FH	Fluoroscopic Shots 2.76±0.72 Guides 3.97±0.94 FH	100% Grade 2 (<2 mm)	95.68%
(Sugawara et al., 2017)	2 to 3 days	$100(Material cost of one set of SGTs and vertebra model)	–	Reduce	100%	–
(Sugawara et al., 2018)	2–4 days	For 10 levels of fixation (20units), the the total cost of screw guide templates and a spine model was $120 to $280.	Reduced	Reduced	98.5% without cortical violation Grade 0	–

(*continued on next page*)

Table 1B (*Continued*)

Authorsand year	Design and Manufacturing time	Cost	Operative time (minutes)	Intra SurgicalRadiation	AccuracyGuides(>2 mm)	AccuracyFree-Hand
(Guo *et al.*, 2016)	2–3 days	–	2.3 ± 0.76 min/screw Guided 4.5 ± 1.39 min/screw FH	Fluoroscopic Shots 3.1 ± 1.01 FH 0.4 ± 0.8 Guided	95.8%–100% Grade 1 (within pedicle)	72.7–90.1%
(Guo et al., 2017)	–	–	10.73±2.17 min/2–4screws Guided 27.70±5.38 min/2–4screws FH	Fluoroscopic Shots 10.95±1.74 Guided 40.35±7.65 FH	94.6% Type II <1 mm	70.27%
(Wang et al., 2017)	–	–	–	–	100% Withing the pedicle	85% Cortex perforation
(Liu et al., 2017)	1–2 days	$290 (par template)	234.0+−34.1 min	–	93.8% Grade 1 < 2mm	78.8%
(Azimifar et al., 2017a)	–	–	–	–	93.63% <1mm	–
(Alpizar-Aguirre et al., 2017)	48 h	$ 500 per case	Potential reduction	Pre-surgical Low dose Intra surgical Only at the end of the surgery	96.6%	–
(Yu et al., 2017)	–	–	–	–	96.3% < 2mm	–
(Zhang et al., 2018)	–	–	–	–	98.1% <1.1mm	–
(Pan et al., 2018)	3 days	–	283+- 22.7 min with Guide 285+−25.8 min FH	–	96.7% Grade 1 < 2mm	86.9%
(Wu et al., 2018)	–	–	Shorter than other methods	–	94.7% Grade 0	–
(Kim et al., 2018)	1 day	$10 for each template,	1–2 min per level	–	95% Class 2 < 4 mm	–
(Chen et al., 2019)	–	4500 Ren Min Bi $ 636,11	–	–	97.1% < 2 mm	–
(Cecchinato et al., 2019)	–	–	6 min/screw Guide 9 min/screw FH	Effective dose 2.15 mSv Dose reduction 88% compared to 0-arm 17.90 mSv	90.2% Grade 0	83.1%
(Naddeo et al., 2019)	1.5 h (design and manufacture)	–	6.25 min/screw Guides 18.75 min/screw FH 66.67%, reduction	Fluoroscopic Shots 3.67 Guided 20.17 FH reduction of 81.82%	87.5% class 1 <2 mm	–
(Garg et al., 2019)	10–12 h	–	235.5 min with guide 298.5 min FH	Fluoroscopic Shots 5.7 Guided 11.9 FH	91.2% Grade 1 <2 mm	82.6%
(Tu et al., 2019)	–	–	5.68 +- 3.22 h	–	93.98%	–
(Nanni et al., 2019)	–	–	–	–	100%	–
(Marengo et al., 2019)	–	Lower cost than other navigation systems	–	Intra surgical Dose 0.53 mGy/cm2.	96% Grade *A* <2mm	-
(Matsukawa et al., 2019)	3 weeks	$200 1 segment	–	–	97.5% Grade A 0–2mm	–
(Shah et al., 2020)	–	–	90±30 s/screw Guided 120±28.28 s/screw FH	–	75% Class 2 <2 mm	62%
(Vissarionov et al., 2020)	–	–	–	–	96.3% Grade 1<1 mm	78.8%

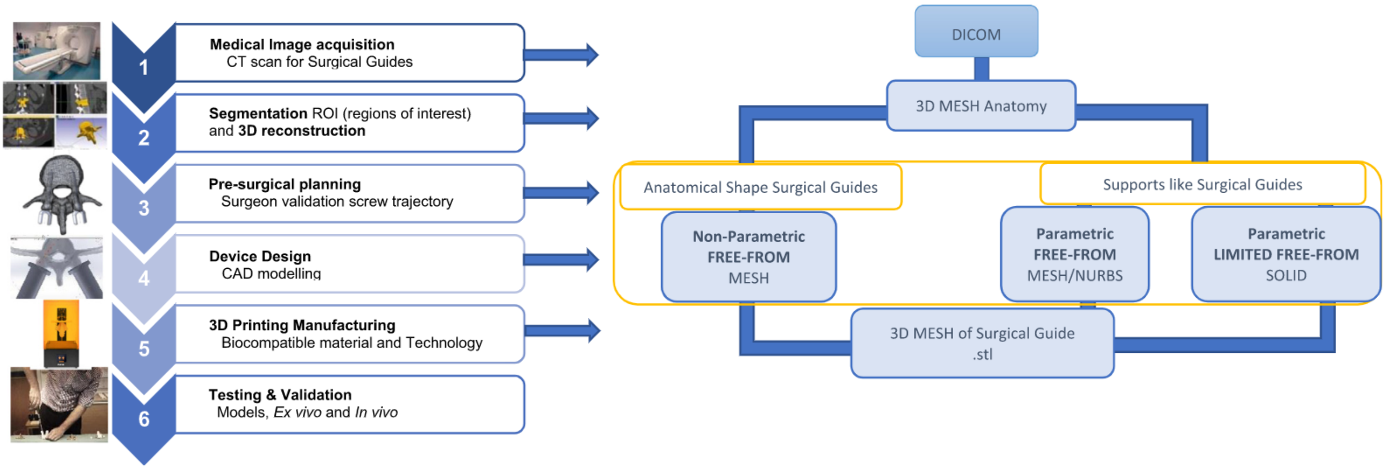


Fig. 2. Design and manufacturing workflow of a 3D printed patient-specific guide for pedicle screw insertion.

3.1.1. *Image acquisition*

Image acquisition is the first step in PSSG design. Computer Tomography (CT) is the preferred imaging method for the basis of PSSG development due to its ability to delineate bone from soft tissue at high resolution. The imaging parameters required vary based on the CT scanner used. The most common parameter for CT image acquisition based on previous publications include pixel matrix (0.35 mm), slice thickness (0.625 mm), no gantry tilt, the smallest field of covering the region of interest, with no file reformatting and exported as uncompressed DICOM files [34–36]. Additionally, it is necessary to pay attention to some fundamental common errors during CT scanning acquisition like the signal to noise ratio, patient movement, limited Field of View (FOV) and distortion [34,37,38]. Hence, 3D reconstructions must be supervised by a specialised surgeon and radiologist to distinguish bony malformations related to the patient pathology from imaging artefacts that compromise image quality.

3.1.2. *Image reconstruction*

This is the second step in PSSG design. After image acquisition, 3D model generation from DICOM data is performed by the process of segmentation and 3D reconstruction. Segmentation and 3D reconstruction can be automated with standardised CT acquisitions but in patients undergoing revision surgery the artefact from metalwork necessitates manual segmentation or corrections to be applied. Common pitfalls are over segmenting or under segmenting the regions of interest. For this, it is advised to follow the Hounsfield Units (Hu) for bone as a reference. Various open-source (3D Slicer, OsiriX) and commercial software (Simpleware Scan-IP, Mimics, Rhino3DMedical) are reported in the literature for image segmentation and reconstruction. Image segmentation and reconstruction is a critical step as it lays the foundation for subsequent screw guide design, conformity to the bone and ultimately the overall accuracy of screw placement.

3.1.3. ***Pre-surgical planning and CAD modelling***

Virtual surgical planning allows the surgeon to visualise the trajectory prior to surgery. The planning can be performed either directly by the surgeon or an engineer under surgical guidance. It is important to differentiate between Solid modelling or Mesh modelling depending on the guide design (Fig. 2).

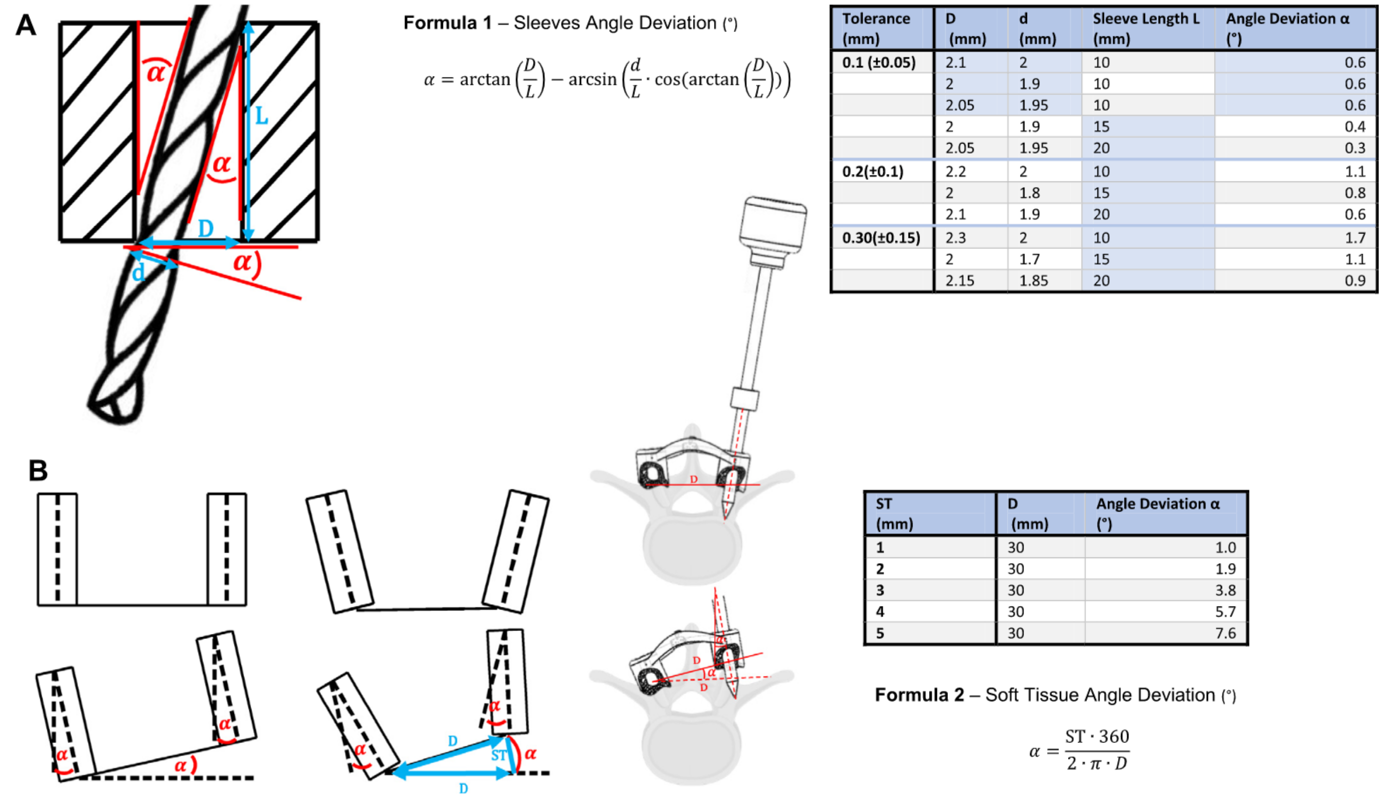
In the studies reviewed, basic designs such as anatomical shape-based designs (Full contact guides) were performed within the segmentation software or other basic mesh modelling software as they consist of extruding the mesh of the posterior surface of the vertebra and adding two sleeves corresponding to the screws trajectories. On the other hand, support based surgical guides (Medium and Low contact) are more complex designs requiring several Boolean operations within solid parametric modelling software such as Solidworks or Fusion 360. For these designs, Mesh modelling is possible although complex Boolean operations between parts require mesh parametrisation (NURBS conversion), which can be performed with considerably expensive software (Catia, 3-Matic). More affordable parametric Mesh modelling software's (Rhinoceros, Blender) require custom scripting for mesh parametrisation (Grasshopper, Phyton, *C*++).

3.1.4. *Device design*

3.1.4.1. Guiding tool. The choice of the surgical tools is based on the spinal implant system the surgeons use, which determines the surgical technique or steps. Drilling, as a single step is preferred over multistep systems that guide screw insertion as there is no difference in placement accuracy (ranges for Drill guide 83.33–100%, Probe guide 75–100%, Multistep guides 87.5–100%) . Some studies describe drill guides that are used in combination with k-wires and cannulated screw systems. Multistep guides can be time-consuming and lead to non-concentric trajectories. Ideally, one single guide or a guide with concentric sleeves should be utilised where both the drill and screwdriver can be inserted. Most studies use a guide with sleeves but Jiang et al. [39,40] [41,42] used sleeveless or hemicylinder guides which made them compatible with any commercial spinal system and added the possibility of modifying the trajectory in the OR.

None of the studies reviewed included information about the tolerances between the sleeve and the surgical tools. The tolerance is the difference between the maximum and minimum limits of a nominal dimension. Both guide sleeves and drill will have tolerances given by the 3D printing technology and material used. The length of the sleeve could be variable in certain guide designs thus it is important to keep a range of acceptable angle deviations within a determined range of tolerances and sleeve lengths (Fig. 3A). Another important parameter is the deviation of the surgical guide caused by the soft tissue. Angle deviations caused by the soft tissue are much greater than those caused by the sleeve tolerances (Fig. 3B).

3.1.4.2. Contact. The ideal design needs to offer a unique fit with no motion and minimum soft tissue dissection. Azimifar et al. classified contact systems into Low and Full contact [43]. We added a third category: Medium Contact (Table 2). Full contact guide design conforms directly to the anatomy of the vertebra and requires a large amount of bone exposure. This is both time-consuming and adds to patient pain. Medium and Low contact approaches may overcome this but multiple design iterations are required to ensure minimum stability. Multi-level guides are more stable but should be used in patients with stiff curves that have low motion between vertebrae or they could



Formula 1 – Sleeves Angle Deviation (°)

$$\alpha = \arctan\left(\frac{D}{L}\right) - \arcsin\left(\frac{d}{L}\cdot\cos\left(\arctan\left(\frac{D}{L}\right)\right)\right)$$

Tolerance (mm)	D (mm)	d (mm)	Sleeve Length L (mm)	Angle Deviation α (°)
0.1 (±0.05)	2.1	2	10	0.6
	2	1.9	10	0.6
	2.05	1.95	10	0.6
	2	1.9	15	0.4
	2.05	1.95	20	0.3
0.2(±0.1)	2.2	2	10	1.1
	2	1.8	15	0.8
	2.1	1.9	20	0.6
0.30(±0.15)	2.3	2	10	1.7
	2	1.7	15	1.1
	2.15	1.85	20	0.9

ST (mm)	D (mm)	Angle Deviation α (°)
1	30	1.0
2	30	1.9
3	30	3.8
4	30	5.7
5	30	7.6

Formula 2 – Soft Tissue Angle Deviation (°)

$$\alpha = \frac{ST \cdot 360}{2 \cdot \pi \cdot D}$$

Fig. 3. A. Formula 1 to calculate the maximal angle deviation (α) given the drill minimal diameter (d), the maximal inner diameter of the sleeve (D) and length of the sleeve (L). The angle of deviation will vary depending on the manufacturing tolerance applied on the sleeve (D) or drill (d) and length of the sleeve (L). Angle of deviation decreases for smaller tolerances and for longer sleeves (L). Examples of angle deviation for probe, screwdriver and drill.

3.B Formula 2 to calculate the angle of deviation given by the arch length (ST) of a circumference of radius (D). Arch length is the soft tissue thickness (ST) and D the distance between two sleeves.

lead to malposition (Table 2). Unilateral guides have been designed in a Full contact approach. A considerable number of authors have explored the use of unilateral guides [32,33, 44–47]. K. Shah [48] used unilateral multi-level guides. Van Brussel [49,50] also introduced the concept of the 'knife-edge' which avoids the guide from slipping as well as decreasing conformity error [29,38,50,51,53–54]. Some authors, however, have reported knife-edge designs to be less intuitive . Furthermore, in degenerative and revision cases, contact landmarks could be destroyed reducing guide stability.

A bone-guide offset might be necessary for Full contact approaches. Additionally, probe, drill or screwdriver tools can produce guide levering. Holding the guide during insertion or adding a temporary fixation or handle could minimise this [51, 52]. The spinal system tools could also serve to anchor the guide.

3.1.4.3. Anatomical landmarks. An accurate selection of anatomical landmarks is necessary to ensure PSSG visibility and stability during surgery. The most common surgical technique used for pedicle screw insertion is the Free-Hand technique (FH). The landmarks that are typically exposed during FH surgery include the lamina, facet joint, *pars articularis* and transverse process (Table 3). At least 6 contact points are needed to limit 6 degrees of freedom (Fig. 4). To reduce the number of supports needed for contact, designs can incorporate temporary fixation methods that serve to pin the guide to the vertebra. The choice of landmarks will determine the guide visibility and stability. Fig. 5 summarises common landmarks used following analysis of the publications from Table 1A. Laminae, the upper part of the spinous process and transverse process (TP) are among common landmarks used for PSSG and provide greater stability during surgery. Although the lamina is easily exposed with open approaches, it can be hard to reproduce in the presence of metalwork. Further analysis on this can be found in Table 3. A consistent landmark choice can help with the design reproducibility. M. Takemoto [55] did a segmentation reproducibility analysis to select the landmarks. When landmarks are distorted for clinical reasons, alternative landmarks have to be used, which may change the guide design significantly and their stability should be tested before the surgery.

Table 2

Contact design approaches classification. Full contact, Medium contact, Low contact guide designs classification appearing in literature. 3D printed patient-specific guide for pedicle screw insertion.

Contact approaches	*Full contact*	Anatomical shape
	Medium contact	Support like and anatomical Contact areas
	Low contact	Support like Contact points
	Multi level guide	Fits multiple vertebrae at the same time
	Unilateral guide	Fits only one side of the vertebrae
	Knife-edge	It a especial support, V-shaped
	Temporary fixation	Guide fixation with k-wire or additional screws

3.1.5. 3D printing. PSSG manufacturing is the next step once the guide has been designed. 3D printing technology has been easily adopted for screw guide manufacturing because of its ability to custom manufacture devices on demand. Various types of 3D printers and materials have been used for screw guide fabrication (Tables 1 & 4). Amongst these, SLA and SLS have higher printing resolution (~0.025 mm) compared to FFF (~0.15 mm). The desktop printers resolution available in the market are lower than CT scan resolutions, therefore resolution falls into the quality of imaging [56].

3.1.6. Testing and validation

Three types of study model have been explored to validate the accuracy of PSSG in the literature. This involves 3D printed dry

Table 3
Landmarks and related features to Soft Tissue removal, exposure during Free-Hand technique, Guide landmark and CT imaging reproducibility.

1. Laminae	*Soft tissue removal*	Easy
	Free-Hand exposure	Yes
	CT imaging reproducibility	Easy (in absence of metalwork)
2. Upper part of Spinous process	*Soft tissue removal*	Difficult
	Free-Hand exposure	The supraspinous ligament is usually preserved C1 has no spinous process C2-C6 can appear bifid
	CT imaging reproducibility	Hard (cartilaginous)
3.TP	*Soft tissue removal*	Easy
	Free-Hand exposure	Not fully exposed. Used to determine pedicle angulation in TL Could be encroached with the ribs in severe deformities.
	CT imaging reproducibility	Easy
4.Base of TP	*Soft tissue removal*	Easy
	Free-Hand exposure	Used to determine pedicle angulation in TL Small or absent in C Could be encroached with the ribs in severe deformities.
	CT imaging reproducibility	Easy
5.Inferior Articular process	*Soft tissue removal*	Not easy to remove (ligaments)
	Free-Hand exposure	Usually exposed to determine pedicle angle (L) Broken to give access to cancellous bone (L) Not visible in C and T
	CT imaging reproducibility	Difficult (cartilage, osteophytes)
6.Superior Articular process	*Soft tissue removal*	Difficult (ligaments)
	Free-Hand exposure	Landmark to determine pedicle angle (L) Broken to give access to cancellous bone (L) Not visible in C and T
	CT imaging reproducibility	Difficult (cartilage, osteophytes)
7. Sides of the spinous process	*Soft tissue removal*	Easy
	Free-Hand exposure	The midline of the spinous process shows pedicle angulation
	CT imaging reproducibility	Easy

C: Cervical, T: Thoracic, L: Lumbar.

models, cadaveric models and patients. The number of cadaveric studies, however, remains small. All the cadaveric studies were performed on specimens without spinal pathologies. The majority of reported studies are in patients. 33 out of 47 reviewed studies were performed in patients, with a minimum of 4 and a maximum of 813 inserted screws per study (see Table 1A). Study types included clinical studies, case-studies, case-series and randomised control trials. A variety of anatomical abnormalities from different scoliosis types (idiopathic, congenital, neuromuscular, and syndromic), kyphosis, degenerative diseases like spondylolisthesis, osteoporotic, arthritis, Ossification of the posterior longitudinal ligament (OPLL), dislocations and tumours and revision surgeries are investigated. Only a handful of studies included paediatric patients, this could be due to limited access to these patient groups and ethical reasons [40,44,57,58].

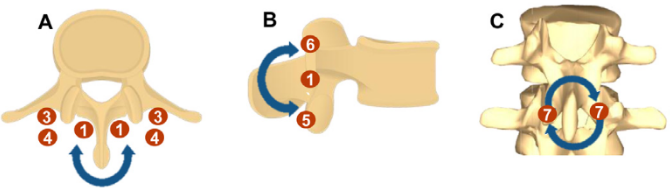


Fig. 4. Six Degrees of freedom. Two per view (Axial, Sagittal and Coronal).

A. TP(3), base of TP (4) and Laminae (1) provide rotational stability in the axial plane.

B. Superior (6) or inferior (5) articular process and Laminae (1) limited sagittal rotation.

C. Sides (7) and upper part (2) of spinous process landmark provides rotational stability in the coronal plane.

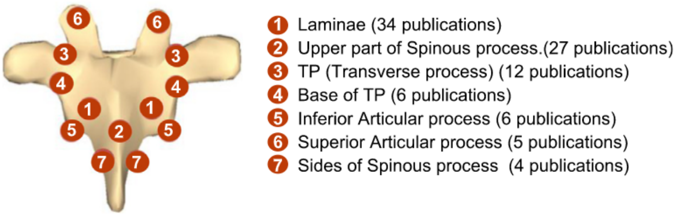


Fig. 5. Landmarks used in the studies. Numerical classification and amount of studies using that landmark.

4. Clinical and economic benefits

Table 1B and 4B summarises clinical and economic benefits based on previous publications. However, not all studies captured clinical and economic benefits and thus inconsistency in data collection makes it difficult to draw definitive conclusions on PSSG benefits.

4.1. Clinical benefits

Clinical benefits of PSSG are being identified in terms of radiation exposure, operative time and pedicle screw placement accuracy. Below we discuss these points in detail.

4.1.1. Radiation exposure

Repeated exposure to intraoperative ionising radiation remains a major concern for children as well as adult patients during spinal surgeries [21–25]. The Use of PSSG has the potential to reduce total radiation exposure compared to its fellow guided technologies since a presurgical CT scan happens once whilst an intraoperative CT is needed for image-guided or robot-assisted procedures. These may need to be repeated when recalibration is necessary. Nevertheless, some intraoperative radiation is still advised especially in the early stages of guide usage. One fluoroscopic image is recommended to inspect the guide positioning before drilling to check the trajectories and one for final assessment of the inserted screws. As surgical confidence grows, however, this can be reduced further, making surgeries safer in the long run. Overall, a significant reduction in the total radiation exposure during spinal surgeries is reported when using the

PSSG. In recent publications, low dose CT scan are also been explored for guide design to reduce intra-operative ionising radiation [29,52,53,59]. However, these studies remain limited and thus offer a further reduction in CT radiation.

4.1.2. Operative time

Comparative and randomised studies quantified the operative time between cases using the PSSG and Free-hand technique. Overall, these studies show positive results reducing the 1–2 min per level or 30 min of average operative time in comparison with Free-hand (Table 1B), while other guided methods require higher times and human resources due to a more complex technology set-up. Overall, time of soft tissue exposure for guide fitting can increase while the screw placement decision making time can decrease. Significant time could also be saved due to the decreased need for intraoperative imaging.

4.1.3. Pedicle screw insertion accuracy using pssg

The intended use of the guides is to increase the pedicle screw insertion accuracy compared to the Free-hand and other technologies. Although there are various grading systems, it is considered to be clinically safe screws with a cortical breach below 2 mm. The Free-hand anatomical trajectory is the gold standard but many other specialised trajectories that require specialisation could find their potential with the PSSG. Some spinal deformity patients have thin pedicles and a cortical breach is inevitable. Other patients with poor bone quality could require intended cortical breaches to enhance the pull-out strength of the screws.

Over the experimental studies, the accuracy of the guides was compared with the accuracy of the virtual planning used for its design. Overall, PSSG showed accuracies over 90% of the inserted screws while Free-hand was between 50 and 87% along with the comparative and randomised studies (Table 1B). PSSG can improve the accuracy and the consistency of pedicle screw insertion while allowing the performance of specialised trajectories without the need for extensive training to offer a more personalised surgical treatment to the patients.

4.2. Economic benefits

Without economic benefits, it is hard for any new technology to be adopted and translated into clinical use. It is important to look at PSSG in terms of their cost and indirect cost saving in terms of time saved on delivery, OR time. As some of this data is not directly documented in the literature, manufacturing cost and delivery time have been evaluated and discussed as an indication of economical benefits.

4.2.1. Cost

A variety of screw guide systems are used, it difficult to state the actual cost per guide. However, rage can be defined between $4 up to $500. The cost of PSSG will be dependent the number of guides to provide together with an anatomical model to check the guide positioning if necessary. From Table 1B, is clear that cost was proportional to the type of 3D printing technology and materials used. SLS and SLA being more expensive compared to FFF. However, other costs include the CT imaging and the designing cost of the engineer which are significant cost of the design process, followed by the type of 3D printing technology used and material.

As these costs vary based on geographical locations, the cost of PSSG has the potential to be tailored to local needs and demands. Nevertheless, the overall cost of PSSG for spinal procedures are in the range of any implant or instrumentation. This device can have a significant impact on healthcare providers that don't have access to Navigation and Robotic guided technologies.

4.2.2. ***Manufacturing and delivery time for PSSG***

Manufacturing and delivery time is crucial for any patient-specific solution, as this has a direct impact on speed and quality of care for the patients. The design and manufacturing time varied from 4 h up to 3 weeks based on the complexity of the case and type of guide designs. It includes the time required for all the steps in the process described above including imaging acquisition and reconstruction, pre-surgical planning, design and manufacturing, sterilisation, and delivery. There is no consistency in reporting of this data in the literature and thus direct comparison is unavailable. Nevertheless, if the PSSG are designed and manufactured at the hospital can significantly save time in data collection, virtual surgical planning validation and delivery.

5. Future direction

5.1. ***Role of minimal invasive PSSG***

Surgeons that seek to minimise tissue trauma undergo specialised training in minimally invasive surgery (MIS) and MIS PSSG have been described (Table 4A and 4B). The Australian company *Anatomics* has taken the lead with their system *SpineBox [60]*. However, this remains largely an unexplored area. MIS PSSG have the potential to improve the accuracy rates and decrease radiation exposure similar to posterior open surgery screw guides, although further studies are needed in this area.

5.2. ***Automation of pre-surgical planning and guides CAD modelling process***

PSGS are custom made medical devices, they are made on an individual basis for every patient. Custom design is a time-consuming process and requires advanced planning. There is potential to save significant time during the virtual surgical planning phase which is an important step necessitating close communication between engineering and surgical teams. Screw trajectory automation during virtual surgical planning can shorten the development time of the PSSG [61–64]. Artificial intelligence (AI) can play a vital role during this process. The algorithms are based on deep learning of previous surgeons performance [65] or intrinsically based on the anatomical features of each vertebra [66]. Algorithms based on deep learning of previous successful surgical performance are able to suggest multiple solutions but are highly dependent on the quality of data. Algorithms based on statistical shape analysis of each vertebrae are more precise but they require a higher degree of manual programming and initialisation [67,68]. Both of these approaches are feasible and can provide faster surgical planning and guide design. However, further research and a close collaborative approach between the surgeon, computer scientist and biomedical engineer are required to develop this approach.

As mentioned in Section 3.1.3 affordable parametric Mesh modelling software's (Rhinoceros, Blender) require custom scripting (Grasshopper, Phyton, *C*++) to work with bigger meshes and only parametrise what is of interest. This allows the design of several surgical guides at the same time enabling a semi-automation of the CAD modelling process, which could significantly improve the design time and thus engineering cost for PSSG.

6. Conclusion

PSSG for pedicle screw insertion are a new technology emerging from the 3D printing revolution that started over a decade ago. They are an alternative to image-guided and Robotic Guided pedicle screw insertion. The design of these Surgical Guides is especially challenging compared to other analogue equivalents in other joints of the musculoskeletal system due to the complex posterior bony surfaces

Table 4A
Methods publications Patient-Specific Surgical Guides (PS SG) for Minimal Invasive spinal fusion surgery.T: Thoracic, L: Lumbar FFF: Fused Filament Fabrication, SLA: Stereolithography SLS: Selective Laser Sintering.Anatomical Landmarks (also in Fig 5 below) – 1: Upper part of Spinous process. 2: Sides of Spinous process 3: TP (Transverse process) 4: Base of TP 5: Superior Articular process 6: Inferior Articular process 7: Laminae.

Authors and year	Study specimen	SpineLevel	Number of Spines	Screws	Guiding tool	Anatomical landmarks	CT ImagingSlice thickness	3D Printing TechnologyMaterial
(Ge et al., 2018)	Cadaveric	L	12	120	Drill	–	-	SLS Polyamide
(Wang et al., 2018)	Animal cadaveric	L	15	150	K-wire	7,3	0.625 mm	Acrylate resin SLA
(Thayaparan et al., 2020)	Patient	L	129	639	Jamshidi needle	7,2,1 stereotactic portholes, pedicle fiducials, and radiographic landmarks.	- Prone	SLS nylon-12 (PA2200)
(Li et al., 2020)	Cadaveric	T L	6	96	Puncture needles	–	- Prone	FFF PLA polylactic acid

Table 4B
Results publications Patient-Specific Surgical Guides (PS SG) for Minimal Invasive spinal fusion surgery.

Authors and year	Design and Manufacturing time	Cost	Operative time	Intra SurgicalRadiation	AccuracyGuides(>2 mm)	AccuracyControl group
(Ge et al., 2018)	–	–	–	-	91.7% guides Grade 2 < 2mm	75%.
(Wang et al., 2018)	–	–	Mean operative time per vertebrae 79.4 ±15.0 s	Fluoroscopic shots/vertebrae 2.1 ± 0.8 times	Planning 0.8 ± 0.5 Postoperative 0.9 ± 0.5	-
(Thayaparan et al., 2020)	2 weeks	Less than the cost of single-use consumables required for 3D navigation.	Mean operative time 153 ± 44 min	DAS 1333.10 ± 670.6 cGycm^2 Fluoroscopic time 57.2 ± 23.7 s	97.8%	-
(Li et al., 2020)	-	-	24.6 ± 7.9 s	-	98.6%	-

of the spine, the risk of neurological damage and the number of guides required for a single intervention. Furthermore, PSSG is dependent on multiple technologies that were limiting their further development. The required amount of computational power and engineering time has kept the PSSG behind the image-guided technologies (CT guided and fluoroscopic). As computer graphics has been evolving, faster and more accurate software have emerged for CAD mesh modelling. In parallel, CT medical imaging has been increasing the quality of image generation and optimised the radiation doses since it became widely available in the '80s. Hence with the upcoming artificial intelligence, automation of processes will speed up the workflow.

This review shows that the PSSG has now been used in an extensive range of spinal pathologies. Although it remains uncertain whether guides can be used on osteoporotic, tumour or fracture cases where the bone quality can cause poor image acquisition and if it can withstand the applied forces of the guide onto the bone [47,59,69]. PSSG has been efficiently used in specialised screw trajectories at the cervical level, cortical trajectories and even in paediatric patients with severe deformities [38,54,70]. The guides have reported a benefit in complex spinal deformities that require guided technology, reaching consistent accuracy rates on the range of Navigation and Robotic techniques. One of the major advantages that PSSG have is that the surgical planning is done before the surgery, minimising fatigue, decision making and surgical time which is one of the significant costs in secondary care. This technology is more economical than other guided technologies, being on the price range of surgical instrumentation that will not represent an impact on the hospital's budget while saving in other areas like intraoperative imaging.

However, among the limitations, once manufactured, it is not possible to change the planned trajectory for PSSGs intraoperatively, although multiple sleeves trajectories could be designed to mitigate this problem. Also, it is vital to re-evaluate the standard surgical care, so that fluoroscopic shots pre and post-operatively do not surpass a pre-operative CT radiation necessary for manufacturing the guides. Similar to other navigation technologies, surgeons still need to follow their clinical expertise to insert the screws, however, the learning curve could be shortened.

While there are clear clinical and economic benefits, most published studies are case reports and further multicentral randomised trials to quantify surgical time and cost benefits of this technology will solidify its place in spinal surgery.

Declaration of Competing Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

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