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Review Article

3D printing in orthognathic surgery — A literature review

Hsiu-Hsia Lin [a], **Daniel Lonic** [b,*], **Lun-Jou Lo** [c,**]

[a] *Craniofacial Research Center, Chang Gung Memorial Hospital, Chang Gung University, Taoyuan, Taiwan*
[b] *MFACE KieferGesichtsZentrum Munich, HELIOS Hospital Munich West, Munich, Germany*
[c] *Plastic & Reconstructive Surgery, Craniofacial Research Center, Chang Gung Memorial Hospital, Chang Gung University, Taoyuan, Taiwan*

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With the recent advances in three-dimensional (3D) imaging, computer-assisted surgical planning and simulation are now regularly used for analysis of craniofacial structures and improved prediction of surgical outcomes in orthognathic surgery. A variety of patient-specific surgical guides and devices have been designed and manufactured using 3D printing technology, which rapidly gained widespread popularity to improve the outcomes. The article presents an overview of 3D printing technology for state-of-the-art application in orthognathic surgery and discusses the impacts on treatment feasibility and patient outcome. The current available literature regarding the use of 3D printing methods in orthognathic surgery including 3D computer-aided design/computer-aided manufacturing, rapid prototyping, additive manufacturing, 3D printing, 3D printed models, surgical occlusal splints, custom-made guides, templates and fixation plates is reviewed. A Medline, PubMed, ProQuest and ScienceDirect search was performed to find relevant articles over the past 10 years. A total of 318 articles were found, out of which 69 were publications addressing the topic of this study. An additional 9 hand-searched articles were added. From the review, we can conclude that the use of 3D printing methods in orthognathic surgery provide the benefit of optimal functional and aesthetic results, patient satisfaction, and precise translation of the treatment plan.

* Corresponding author. MFACE KieferGesichtsZentrum Munich, HELIOS Hospital Munich West, Am Schützeneck 8, Munich, 81241, Germany. Fax: +49 89 8292 4422.
** Corresponding author. Department of Plastic & Reconstructive Surgery, Chang Gung Memorial Hospital, 5 Fu-Shin Street, Kwei Shan, Taoyuan, 333 Taiwan. Fax: +886 3 3271029.
E-mail addresses: lonic@mface.de (D. Lonic), lunjoulo@cgmh.org.tw (L.-J. Lo).

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Introduction

Orthognathic surgery (OGS) is used to correct maxillary and mandibular deformities from dental malocclusion, diseases, injuries, and defects in the maxillary and mandibular deformity as well as to improve the facial appearance. Traditional treatment planning for OGS depends on clinical examination, two-dimensional (2D) cephalometric analysis and the study of plaster dental models. However, 2D cephalometric analysis has known limitations such as projection and identification errors, especially in a patient with facial asymmetry.[1–6] Recent advances in the field of three-dimensional (3D) imaging using cone-beam computed tomography (CBCT) have led to the development of computer-assisted OGS, in which detailed presentation of the craniofacial complex and enhanced analysis of surgical planning lead to improved predictability of surgical outcomes.[7–21] The application of computer-aided design and computer-aided manufacturing (CAD/CAM) has rapidly developed and spread widely from industry to medicine.[22–29] In the medical field, such as traumatology, orthopedics, neurosurgery, implant dentistry, plastic surgery, craniomaxillofacial surgery and OGS, 3D printing is commonly used to create 3D models from digital images in surgical planning, customized surgical devices and for doctor-patient communication.[30–39] Over the past 10 years, the development of 3D printed models and patient-specific guides has improved surgical planning as well as the transfer of the surgical plan into the operating room for a better surgical result. A steadily increasing number of studies has reported and investigated the clinical experiences and effectiveness of 3D printing applications for OGS.[40–43] In general, the clinical applications of 3D printers in OGS include the production of occlusal splints, osteotomy/cutting guides, repositioning guides, spacers, fixation plates/implants and 3D printed models.

In this study, we present a comprehensive review and summarize the latest advances in the above-mentioned applications of 3D printing technology in OGS, and provide updated information for clinicians to accurately implement the use of 3D printing for the improvement of treatment outcomes.

Materials and methods

To identify relevant articles for this review, PubMed, Medline, ProQuest and ScienceDirect searches were performed for English-language literature published over the last 10 years. The search items used in this article were three-dimensional, 3D printer, printing, custom-made, computer assisted, computer aided design, computer aided manufacturing, CAD, CAM, surgical guide, splint, wafer, templates and miniplates in combination with maxillofacial, craniofacial and orthognathic surgery. The type of OGS includes LeFort I osteotomy, bilateral sagittal split osteotomy (BSSO) and genioplasty. A total of 318 articles were found from 2007 to present, out of which 126 publications were considered potentially relevant. 57 duplicated articles were removed. The remained reference articles were hand-searched and additional 9 articles were identified.

Results

In total, 78 articles were selected for full text analysis describing the various clinical applications using 3D printing in OGS. Fig. 1 showed the search results. An overview of the characteristics of the reviewed articles was shown in Table 1.

Summary of reports

Occlusal splint

The conventional production of an occlusal splint involves the use of plaster models, face-bow and articulator. However, the manual-based procedures are time-consuming and have shown non-controllable errors and interlaboratory differences. Compared to the traditional method, the digital-based occlusal splint provides high accuracy, reliability and consistency, as well as improved quantitative control and efficiency (Figs. 2 and 3). With the increasing use of CAD/CAM techniques in OGS, various studies reported the use of 3D printed occlusal splints instead of the traditional method for positioning during the surgery. Lauren et al. proposed the first computer-based design and fabrication of flat-plane and full-coverage occlusal splints with guidance ramps, and made the digital splints commercially available.[44] During the beta testing, 150 cases were inquired to provide feedback on the occlusal adjustments. Most of the comments were positive in the 78 responses. Metzger et al., Choi et al., Uribe et al., Scolozzi et al. and Francisco et al. introduced a case study approach using combined data from 3D virtual dental casts and virtual preoperative 3D planning.[45–51] Among these studies, the orthognathic wafers were produced by using a Boolean function of virtual blanks and tooth impressions obtained from 3D virtual model surgery. All of the patients had aesthetic improvement and stable dental occlusion with a high satisfaction rate in the follow-up evaluation, and the total orthodontic treatment time was reduced. Dahan et al., Aboul-Hosn Centenero et al. and Shqaidef et al. reported comparative studies of accuracy between final CAD/CAM occlusal wafers and conventional acrylic wafers.[52–54] The mean distance was large in some landmarks between the conventional wafers and rapid prototypes, and further study is required to assess the difference. Hernandez-Alfaro et al. presented one in vitro and one prospective in vivo study using an intraoral digital scanner instead of dental impressions to obtain surface images of the dental arches. After fusing the scans with the CBCT images of the patients for CAD/CAM intermediate splint generation, the accuracy and reliability of the protocol was assessed.[55] Vector error calculation was below 1.5 mm for both in vivo and in vitro between the virtual intermaxillary position and the intraoperative intermaxillary relationship revealing a high overall accuracy. Schouman et al. proposed a cadaveric study to evaluate the accuracy of CAD/CAM generated maxillary cutting guides and intermediate splints in OGS.[56] Zhou et al. also developed a CAD/CAM intermediate splint for maxillary positioning.[57] Ying et al. reported a prospective study to

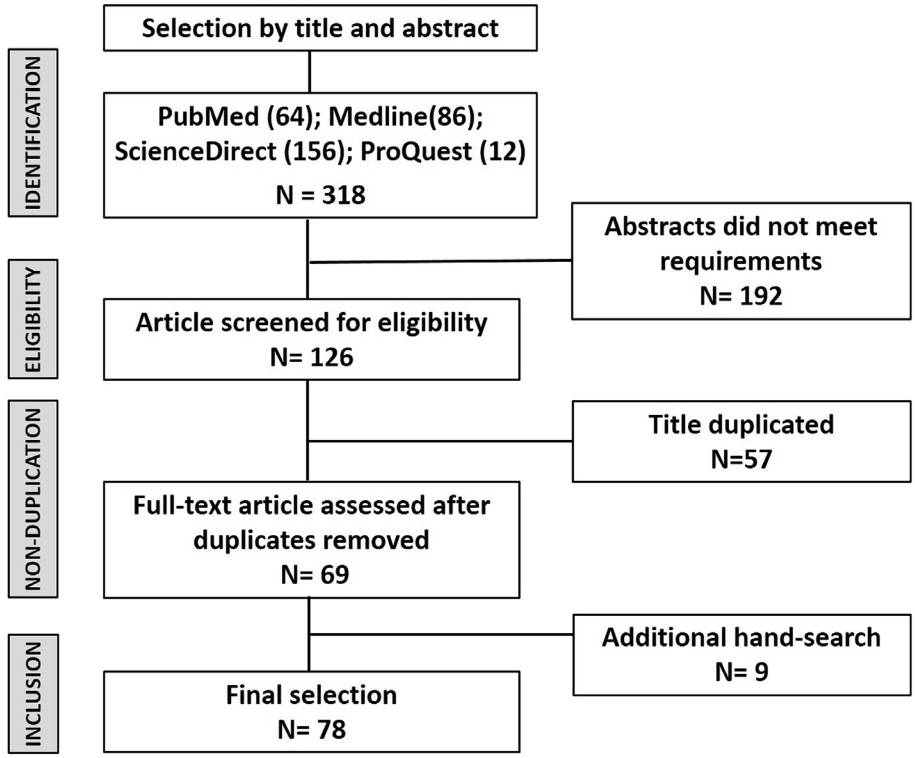

Figure 1 Flow chart of the article selection process.

Table 1 An overview of the disjunctive characteristics of the reviewed articles.

Category	Number of reviewed articles
Occlusal splint	16
Osteotomy guide	18
Repositioning guide	42
Fixation plate/implants	12
Spacer	1
3D models	25

The repeat articles can be categorized into two categories based on text content.

investigate the efficacy of combined guiding templates and splints fabricated by rapid prototyping technique for the correction of facial asymmetry associated with vertical maxillary excess and mandibular prognathism.[58] Vale et al. evaluated the feasibility and precision of 3D virtual planning and production of CAD/CAM surgical splints in one patient with craniofacial macrosomia for predicting the postoperative outcome on hard tissue.[51] Shaheen et al. presented and validated a protocol for the design and 3D printing of final digital occlusal splints based on 3D virtual surgery planning.[59] They reported that facial asymmetry was improved in all patients with satisfactory outcome, and the protocol had an acceptable clinical error margin; but also indicated that the technology could be future improved. Most studies have agreed that CAD/CAM occlusal splints with no modifications compared to traditionally manufactured occlusal splints provided a reliable substitute for OGS.[54,60,61] Lin et al. presented an innovative modification of the CAD/CAM occlusal splint with attached auxiliary bars for single-splint two-jaw OGS to provide the surgeon with significantly better intraoperative guidance and a subsequent improvement of surgery outcomes.[62] The details and postoperative outcome evaluation of the different models of CAD/CAM occlusal splints of the included studies is shown in Table 2.

Osteotomy guides and repositioning guides

Osteotomy guides are used to ensure that the osteotomy is placed exactly as in the digital planning, so that the

Figure 2 A 3D printed model for a patient after simulation of 2-jaw orthognathic surgery. The LeFort I repositioning guides and final occlusal splint were designed and printed.

Figure 3 The LeFort I repositioning guides and occlusal splint were fit into position.

repositioning guide can exactly place the bone segment in the desired position (Figs. 2 and 3). The use of 3D printed osteotomy guides has been reported for BSSO and genioplasty surgery. Zinser et al., Polley et al., Jimenez et al., Peter et al., Zhang et al. and Suojanen et al. introduced the use of surgical guides for condylar position control and inferior alveolar nerve injury prevention during BSSO.[63–69] They provided a reliable, innovative, and precise approach for translation of the virtual plan to the operating theater. The linear and angular differences between the virtual and postoperative image models were clinically acceptable. Further studies are required to evaluate the image interference, such as the bony interference at the osteotomy sites. Olszewski et al. first presented a new computer-designed genioplasty guide to transfer the osteotomy line and exact planned position into the operating room.[70,71] Kang et al. and Lim et al. also reported the design and fabrication of a simple surgical guide for genioplasty.[72,73] Li et al. developed and validated a new chin template for a two-piece narrowing genioplasty.[74] Yamauchi et al. used an osteotomy guide fitted on the mandibular incisors for genioplasty.[75] Time spent on the osteotomy and plate bending was reduced during surgery. The results showed that the chin templates were easy-to-use, reducing surgical time, and providing a reliable method to transfer the genioplasty planning. Larger sample and control group were needed to further validate the system. To improve the vertical dimension control of the maxilla, Zinser et al. incorporated a patented three-sequential surgical splint consisting of an occlusal splint, bone attachments, connecting arms, and osteotomy line indicator for translating virtual plans into actual OGS.[63,64] Moreover, a number of studies have evaluated the use of 3D printed repositioning guides as an alternative approach to intermediate surgical wafers for transferring virtual surgical plans into the intraoperative setting. Suojanen et al. and Mazzoni et al. developed an easy-to-use CAD/CAM cutting guide and titanium fixation plate combination to facilitate the intraoperative reproduction of the surgical plan.[69,76] Gander et al. presented an osteotomy guide with definitive drill holes for final placement repositioning guides without the need of occlusal splints.[77] The fitting of CAD-CAM cutting guide and customized titanium plates were accurate for maxilla repositioning without the use of intermediate wafer. Kraeima et al. reported the use of CAD/CAM titanium L-plates with dentition-supported drills to indicate the Le Fort I osteotomy line as well as the drilling sites for splintless surgery.[78] Mean distance between the postoperative result and the preoperative plan was 1.3 ± 1.4 mm, indicating an accurate positioning of the maxilla independent of the condyle or mandible. As mentioned above, the design of the repositioning guide is defined by the position of the osteotomy line, thus making the use of the osteotomy guide mandatory. Another type of repositioning is achieved by moving the bone segment with no relation to the osteotomy line. Bai et al. introduced a pair of CAD/CAM surface templates to reduce the effort, the operation time and possible errors arising from the conventional approach.[79] Maxillary transverse cant and midline deviation were corrected according to the preoperative plan and simulation. Bai et al. also reported a procedure using CAD/CAM guides and pre-bent titanium plates to position the maxillary segment in a fast and accurate manner.[80] Shehab et al. proposed a tooth and bone splint design to guide the maxillary position.[81] Li et al. presented a CAD/CAM osteotomy and repositioning guide combination that did not require traditional model surgery.[82] The paired t-test did not show significant difference between the planned and actual movement in all directions. Polley et al. introduced an occlusal-based ''orthognathic positioning system'' for translating virtual plans to actual orthognathic surgery.[65] Philippe et al. presented the accuracy, outcomes, and complications of the use of computer designed guides and direct metal laser sintering titanium miniplates in OGS.[83] Lee et al. introduced a new CAD/CAM key and keyhole system to simultaneously reposition the maxilla and mandible without an intermediate occlusal splint.[84] Lin et al. designed an easy-to-use positioning guide for the single-splint technique to simplify surgery, reduce operating time, and accurately transfer the virtual surgical planning.[85] Brunso et al. used bone-supported guides and computer designed titanium miniplates to provide position control with considerable surgical accuracy.[86] The novel method provided adequate vertical control and condyle positioning with surgical accuracy. Details and postoperative outcome evaluation for the osteotomy and repositioning guide systems described in the studies are shown in Table 3.

Spacers

To achieve facial symmetry and harmony, "spaces" occur in the LeFort I when lengthening the vertical dimension of the maxilla, in BSSO after the rotation or shifting of the mandible for maintaining or increasing the space in symmetry or cheek contour correction, and in genioplasty in vertical lengthening procedures. These spaces should be maintained as planned during plate and screw fixation. Dumrongwongsiri et al. used different types of customized 3D-printed "spacers" to guide and stabilize the planned

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Table 2 Methods and postoperative outcome evaluation for the CAD/CAM occlusal splint in the studies.

Author and year	Type of study	Sample	Planning time	Duration of surgery	Material cost	Postoperative outcome evaluation
Lauren et al., 2008[44]	Prospective case series	150	NA	NA	NA	During the beta testing, a form was enclosed with all cases requesting feedback on the required occlusal adjustments. Most of the remaining comments were "goods and "averages."
Metzger et al., 2008[45]	Prospective case report	1	NA	NA	€0.20/cc	Image fusion of the preoperative planning and the clinical outcome.
Choi et al., 2009[46]	Prospective case report	1	<50 min	NA	NA	NA
Choi et al., 2012[47]	Prospective case series	18	NA	NA	NA	[a]There was no significant difference in the position of upper dentition after surgical movement between 2.5D-VMS and 3D-VMS in all samples.
Uribe et al., 2008[48]	Prospective case report	2	NA	NA	NA	Superimposition of the virtual plan and the outcome for patient shown that accurate, predictable, and efficient treatment outcomes can be achieved.
Scolozzi et al., 2014[49]	Prospective case report	1	NA	NA	€2000/2 splints	Follow-up at 1 year showed a stable facial cosmetic result, dental occlusion, and no relapse.
Scolozzi et al., 2015[50]	Prospective case series	4	NA	NA	NA	No intra- and/or postoperative complications. All of the patients had stable cosmetic results with a high rate of patient satisfaction at the 1-year follow-up examination.
Francisco et al., 2008[51]	Prospective case report	1	NA	NA	NA	Displacement of selected landmarks from the preoperative situation to the postoperative outcome.
Dahan et al., 2008[52]	Prospective case report	1	NA	NA	NA	NA
Aboul-Hosn Centenero et al., 2008[53]	Prospective case series	16	NA	NA	NA	Different linear and angular measurements from the preoperative 3D images were used to determine the precision of the prediction of results.
Shqaidef et al., 2008[54]	Prospective case series	10	NA	NA	NA	The reliability of the rapid prototype wafer was assessed by evaluating its accuracy in the articulation of the upper and lower plaster study models.
Hernandez-Alfaro et al., 2008[55]	An in vitro and in vivo study	6	NA	136min (110–156) surgery and intraoral scanning	NA	Vector error calculation between the virtually simulated intermaxillary position and the intraoperative intermediate intermaxillary relationship revealed high accuracy.
Schouman et al., 2008[56]	A cadaveric study	1	NA	NA	NA	The 3D translational and rotational differences measured between planned and post-operative mandible and maxilla were found to be within the permitted accuracy.
Zhou et al., 2008[57]	Prospective case series	8	166min (181–141)	NA		The deviations between the actual and planned position and orientation of the maxilla movements were evaluated by root mean square error.

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Table 2 (*continued*)

Author and year	Type of study	Sample	Planning time	Duration of surgery	Material cost	Postoperative outcome evaluation
Ying et al., 2008[58]	Prospective case series	14	NA	NA	NA	Parameters reflecting maxillary canting, ramal inclination, mandibular deviation and chin inclination were measured and compared before surgery, 7 days and one year after surgery. Facial asymmetry was corrected in all patients with satisfactory outcomes.
Shaheen et al., 2008[59]	Prospective case series	20	NA	255min	NA	The mean absolute distance error between the landmarks on the upper occlusion cast and the corresponding landmarks on the upper cast with the digital splint after superimposition was 0.4 mm (0.12—0.88).
Song et al., 2008[60]	Prospective case series	25	NA	NA	NA	[b]Compared the accuracy of model surgery between3D-VMS and MMS. The errors with 3D- VMS (0.00 —0.35 mm) were less than with MMS (0.00—0.94 mm).
Kim et al., 2008[61]	Prospective case series	55	NA	NA	NA	[c]The accuracies of the wafers by DMS were similar to those for wafers produced by manual model surgery (MMS).
Niu et al., 2008[62]	Prospective case series	50	110min (90—120)	NA	NT$24/g	[d]The mean of RMSD values of simulation and postoperative result was 0.46 mm (0.38—0.49).

[a] 3D-virtual model surgery program using combined 3D computed tomography and 3D virtual dental casts. (3D-VMS); A new virtual model surgery program using 2D lateral and posteroanterior (PA) cephalograms and 3D virtual dental models (2.5D-VMS).
[b] Conventional manual model surgery (MMS).
[c] Digital model surgery (DMS).
[d] Root mean square distance (RMSD).

maxillary and mandibular segment position.[87] All spacers were nicely fit in the position during the procedure and easily removed after rigid fixation of bone segments, and the postoperative facial symmetry was significantly improved.

Fixation plates/implants

Suojanen et al. and Mazzoni et al. reported the use of patient-specific titanium plates fabricated by using the EOS Titanium Ti64 system (Electro-Optical Systems) for maxilla segment repositioning and fixation without surgical splints. A Ti6AIV4 alloy is available in a pre-alloy fine-powder form, which exhibits excellent mechanical properties and corrosion resistance, has low specific weight, and is highly biocompatible. The material is particularly suitable for the production of a biomedical implant.[69,76] The approach for the production of the titanium miniplates/guides utilizing a direct metal laser sintering technology by Philippe et al. is similar, but instead of using two independent pieces, they are joined into a single combined titanium implant that acts as both the positioning guide and the custom-made miniplate, but requires a larger access incision.[83] Compared with the sintering technique, layer-by-layer construction is potentially less expensive and faster; on the other hand, it may result in lower rigidity and carries a higher risk of contamination. Brunso et al. examined the stability of miniplates from highly rigid grade 5 titanium (Createch Medical, Mendaro, Spain) milled from a titanium block that were fixed to good quality bone on the anterior midfacial buttress.[86] In contrast to previous studies regarding the manufacturing process of fixation plates, Huang et al. developed an optimal biomechanical miniplate using a 5-axes milling machine. When fixed onto the freed separate maxillary segments of a rapid prototyping model, the plates provided precise positioning/fixation and presented adequate strength/stability in the LeFort I osteotomy.[88] The patient-specific titanium plates provided precise positioning and fixation, as well as delivered adequate strength and stability in LeFort I osteotomy.

3D printed models

The possibility to produce 3D printed models using data form CT images has significantly improved preoperative assessment, orthognathic surgical planning, as well as intraoperative orientation and pre-bending of miniplates (Fig. 4). Mavili et al. demonstrated an increase of accuracy

Table 3 Methods and postoperative outcome evaluation for the osteotomy guide and repositioning guide of the studies.

Author and year	Type of study	Sample	Planning time	Duration of surgery	Material cost	Postoperative outcome evaluation
Zinser et al., 2012, 2013[63,64]	Prospective case series	8	NA	4.5 h ± 30mim	NA	Comparison of linear and angular measurements between planes on preoperative simulated virtual positions and actual postoperative positions.
Polley et al., 2013[65]	Prospective case report	1	NA	NA	NA	NA
Jimenez et al., 2013[66]	Prospective case series	26	NA	NA	NA	25 patientes maintained stability, one patient had massive bleeding infratemporal fossa.
Peter et al., 2016[67]	Prospective case report	1	NA	NA	NA	NA
Zhang et al., 2016[68]	Prospective case series	30	NA	NA	NA	The linear difference between the virtually simulated model and the actual postoperative model is presented.
Suojanen et al., 2016[69]	Prospective case series	32	NA	NA	NA	The fitting of patient-specific 3D printed plates was in most cases so precise that there would be no need for intermediate wafer maxilla repositioning.
Olszewski et al., 2010, 2014[70,71]	Prospective case report	1	NA	NA	<€300/a 3D RP model	The postoperative results of the new technique are promising.
Kang et al., 2014[72]	Prospective case series	15	NA	NA	NA	Use of a stereolithographic surgical guide increased accuracy, but the difference in mean error values between methods was only approximately 0.3 mm.
Lim et al., 2015[73]	Prospective case report	1	NA	NA	NA	NA
Li et al., 2016[74]	Prospective case series	9	NA	NA	NA	The largest linear RMSD between he planned and the postoperative chin segments was 0.7 mm and the largest angular RMSD was 4.5°.
Yamauchi et al., 2016[75]	Prospective case report	1	NA	NA	NA	NA
Mazzoni et al., 2015[76]	Prospective case series	10	NA	NA	€750 (500–1000)	The upper maxilla repositioning represented a promising method to allow accurate reproduction of preoperative virtual planning without surgical splints
Gander et al., 2015[77]	Prospective case report	1	NA	NA	NA	Superimposition of the pre- and post-operative CBCT scans. Only a minimal discrepancy was evident between the postoperative result and the preoperative digital plan
Kraeima et al., 2016[78]	Retrospective case series	3	NA	NA	NA	Measurements on superimposed 3-dimensional models of the preoperative and postoperative cone-beam images.
Bai et al., 2010[79]	Prospective case report	1	NA	NA	NA	NA
Bai et al., 2012[80]	Prospective case report	25	NA	NA	NA	NA
Shehab et al., 2013[81]	Prospective case series	6	NA	NA	NA	The paired t test showed no significant difference between the

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Table 3 (*continued*)

Author and year	Type of study	Sample	Planning time	Duration of surgery	Material cost	Postoperative outcome evaluation
						planned and actual movements in both the vertical and horizontal measurements by comparing the planned and actual movements of the maxilla.
Li et al., 2013[82]	Prospective case series	6	80min (70–95)	160min (120–180)	NA	The mean absolute error of the maxillary position was less than 1 mm, and the maximum error was well-controlled within 1.7 mm.
Philipp[83]	Prospective case report	1	NA	NA	NA	NA
Lee et al., 2015[84]	Prospective case report	1	30min	NA	US$350	NA
Lin et al., 2015[85]	Prospective case series	25	350min (240–360)	30–50 min reduced	US$200	The RMSD values between the surgical simulation and postoperative CBCT models ranged from 0.18 to 0.33 mm in the maxilla and from 0.99 to 1.56 mm in the mandible.
Brunso et al., 2016[86]	Prospective case series	6	110min (90–120)	NA	NT$24/g	The post-operative 3-dimensional reconstructed computed tomography image and the presurgical plan were compared.

in orthognathic surgery and prevention of condylar mispositioning and sag by using life-sized, 3D printed models.[89] Ibrahim et al. analyzed the dimensional error and reproduction of mandibular anatomy in the three rapid prototyping techniques of selective laser sintering (SLS), three-dimensional printing (3DP™) and PolyJet™ models.[90] O'Neil et al. presented a new method for replicating the skull and occlusal surface as an accurate physical model,[91] while Ayoub et al. produced a composite model of a 3D printed mandible bearing plaster teeth for orthognathic surgery planning.[92] Lee et al. compared CAD/CAM facebow-based surgical wafers and bite splints for maxillary OGS performed on rapid prototyping models.[93]

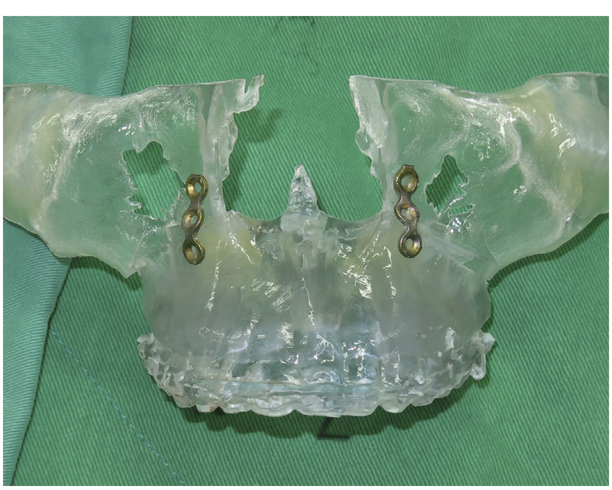

Figure 4 The 3D printed model showing the final position of the LeFort I segment. The model can be used for intraoperative orientation of the maxilla, and for pre-bending of miniplates.

In-house or outsourcing 3D printing

The following factors should be considered when making the decision on creating an in-house 3D printing service versus using outside vendors. Creating an in-house printing setup needs an already existing infrastructure, including experienced CAD/CAM technicians, corresponding software for 3D printing, and 3D printer equipment. This infrastructure requires relatively high initial investments. Outsourcing is a better option for a developing or low-volume center, which could then subsequently shift to an in-house solution by training of technicians and modular upgrade of the hardware. The features of 3D-printing hardware and software are becoming more user friendly and commercially available. In both cases of using in-house or outsourced 3D printing services, good and effective communication between the clinician and the 3D design technician is important. If experienced and skilled CAD/CAM technicians are available in an in-house setting, the whole process from design to manufacturing can be controlled, and processing time can be saved under conditions of ongoing quality control. The hardware requirements highly depend on the resolution, materials and size of the required 3D model. Soft materials or biomaterials are more expensive than regularly used resins. For example, the traditional resin material is enough to create a pre-surgical educational model for the patients or medical students. For an academic and high-volume center however, an in-house facility is mandatory. Currently, the decision as to either provide in-house or choose outsourced 3D printing services is based on the clinical needs, but a medical center can also choose the combination of both services to achieve optimal cost control and convenience.

Discussion

With the steady improvement of its processes and materials, the distribution of 3D printing technology has widely increased in various fields of medicine. Recent advances in 3D imaging, virtual surgical planning combined with CAD/CAM software as well as further developments of 3D printers opened up new possibilities to fabricate more precise patient-specific devices based on patient's 3D digital models for orthognathic surgery. Subsequently numerous studies have demonstrated that 3D printing technologies help the clinician to shorten operative time, increase surgical safety, and improve the predictability of surgical outcomes. This review examined the recent clinical applications of 3D printing in orthognathic surgery that included occlusal splints, osteotomy/cutting guides, positioning guides, spacers, fixation plates/implants and 3D printed models. State-of-the art applications of 3D printing and the impacts on orthognathic surgery were also discussed.

For occlusal splints, previous studies have proposed the use of CAD/CAM occlusal splints as a reliable substitution to address the flaws of laboratory-based methods including non-controllable errors, inter-laboratory differences, high cost and time inefficiency. Moreover, advanced custom-designed CAD/CAM occlusal splints with auxiliary markers have provided significantly improved intraoperative guidance and information to enhance OGS outcomes. The CAD/CAM osteotomy and repositioning guides are used to translate 3D virtual planning to actual OGS for operative simplification and reduction of surgical errors. The guides can be combined or designed as separate units for guiding the osteotomy process followed by moving the bone segment to the planned final position. In recent studies, researchers have investigated the use of 3D CAD/CAM surface templates/guides as an alternative to intermediate surgical splints for guidance of both osteotomy and repositioning as well as translating the virtual plan to actual surgery. However, these assembled products were complicated in design and fabrication and experienced inconvenience or inflexibility during the actual surgery. Therefore, a modular design of repositioning guides with or without corresponding osteotomy guides has been commonly accepted. Promising developments of biomedical printing and direct laser metal sintering technology showed that titanium miniplates could be prefabricated and used for screw fixation after bone repositioning. Additional surgical guidance during orthognathic surgery can be achieved by using customized CAD/CAM "spacers" that maintain the spatial relationship between the bone segments. They provide position control when lengthening the maxilla in LeFort I procedures, when maintaining or increasing the space after rotation or shifting of the mandibular ramus segments in BSSO, and for chin lengthening in genioplasty. This practice helps to improve symmetry in OGS for correction of facial deformity and prevention of postoperative facial asymmetry. In addition to guides, the 3D printed models have been applied to assist the orthognathic surgical planning and doctor-patient communication.

Conclusions

This review reveals that various patient-specific 3D-printed surgical devices are increasingly used in orthognathic surgery, and concludes that it is beneficial to the clinicians and patients. It provides information can be helpful for researchers and clinicians considering the use of 3D printing techniques in OGS. Greater variety of materials with varying characteristics and capabilities of 3D printing technology are being explored. There are still many potential applications for future research and clinical application in orthognathic surgery.

Conflict of interest

The authors have no conflict of interest.

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