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Revolutionizing Oral & Maxillofacial Surgery - Reviewing The Concept Of 3d Printing And Virtual Surgical Planning

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1. INTRODUCTION

Orthognathic surgery, specifically, is a subset of oral and maxillofacial surgery that focuses on correcting diseases and disorders affecting the structure of the jaw and face, sleep patterns, TMJ disorders, malocclusion problems owing to skeletal disharmonies, and other orthodontic problems that cannot be easily treated with orthodontics [1]. These surgeries aim to improve chewing, speaking, and breathing functionality while enhancing the patient's appearance [2]. On the other hand, oral maxillofacial surgery is a broader field that not only includes orthognathic surgery but also concerns the treatment of diseases and injuries of both the functional and aesthetic aspects of the hard and soft tissues of the oral and maxillofacial region [3]. This can range from the removal of impacted teeth and administering of complex facial reconstructions to the treatment of oral cancer, cleft lip and palate, and chronic facial pain disorders. These fields require an in-depth understanding of the interplay between aesthetics and function, and the complex anatomical structures and their relationships in the craniomaxillofacial region [4]. Surgeons specializing in these areas combine their expertise in dentistry, surgery, and general medicine to provide comprehensive care for patients.

Orthognathic and oral maxillofacial surgeries traditionally depend on detailed preoperative planning, including the creation of physical models and utilization of various imaging techniques [2]. Dental casts, cephalometric analysis, and two-dimensional (2D) imaging, such as panoramic radiography, cephalograms, and computed tomography (CT) scans, have been the standard [4]. However, these conventional methods present limitations. While 2D imaging has proven valuable, it does not provide comprehensive three-dimensional details of the patient's anatomy. Similarly, physical models, though helpful, cannot capture the dynamic nature of facial structures and movements [5].

Despite their proven efficacy, these techniques can be quite invasive, with significant post-operative morbidity in some cases [6]. The predictability of outcomes can also be challenging due to variations in healing, relapse, or the lack of precision in executing the pre-surgical plan [6]. Traditional methods come with inherent risks and complications such as infection, bleeding, nerve damage, issues with wound healing,unfavorable bone segment movement, and relapse [5,7]. In severe cases, these complications could lead to a second surgical intervention [8] From a patient's perspective, traditional surgical methods can be intimidating due to the invasive nature of these procedures and the potential for long recovery times. Additionally, the traditional planning process may not allow patients to visualize the intended surgical outcome, leading to potential dissatisfaction with the postoperative results. Traditional methods in orthognathic and oral maxillofacial surgery rely on the surgeon's skill and experience for precision, which can lead to variability in outcomes [6]. Moreover, translating two-dimensional pre-surgical plans into three-dimensional surgical procedures can be challenging and may affect the accuracy of the operation [9]. While experience and skill can help predict outcomes to some extent, the inherent unpredictability of human tissue responses post-surgery often leads to unexpected results [2]. This lack of predictability can result in dissatisfaction from patients who had different expectations of surgical results [9]. Every patient presents a unique anatomical framework and individual needs and expectations. Traditional methods, while customizable to an extent, do not provide the level of personalization and adaptability necessary to meet these varied needs [10].

As medicine moves towards patient-centric care, the demand for personalized surgical methods increases [11]. Surgeons need to tailor surgical plans to the individual patient's anatomy and desired outcomes. The need for greater surgical precision and predictable outcomes is paramount in improving patient satisfaction rates and reducing complications [12]. Utilizing advanced technology can help achieve this by improving surgical planning, execution, and follow-up care. Incorporating 3D technology in surgical procedures can aid in better visualization of the surgical area, enhancing precision during surgery [13]. Furthermore, the ability to simulate different surgical scenarios can lead to better preparedness and more predictable outcomes. By enabling patients to visualize their surgical outcomes beforehand through virtual surgical planning, we can manage their expectations better and potentially enhance satisfaction rates [14]. Moreover, less invasive surgery due to precise planning can lead to quicker recovery times and less post-operative discomfort, further improving the patient experience [15].

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This review seeks to critically examine the evolution and limitations of traditional methods in orthognathic and oral maxillofacial surgery and explore the potential advantages of integrating advanced technological tools, such as 3D technology, into surgical procedures.

2. THE ADVENT OF 3D PRINTING IN MEDICAL FIELD

Three-dimensional printing, also known as additive manufacturing, has emerged as a trans formative technology in the last few decades [16]. The process involves creating
three-dimensional objects from a digital file, typically by adding material layer by layer [17].
Various types of 3D printing exist, including stereolithography (SLA) [18], fused deposition modeling (FDM) [19], and selective laser sintering (SLS) [20], each with its unique strengths and suitable applications (Figure 1).

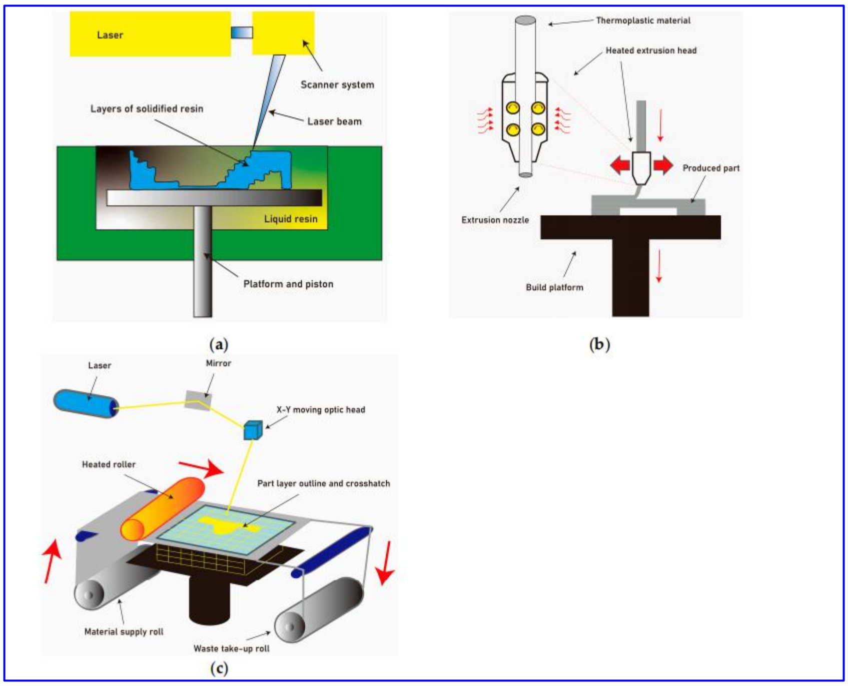

FIGURE 1. There are several forms of 3D printing, such as (**a**) stereolithography, (**b**) fused deposition modeling (FDM), and (**c**) selective laser sintering (SLS), each possessing distinct advantages and appropriate areas of application.

One significant limitation is the relatively long processing time required for the completion of the printing process [22]. Additionally, SLA is limited in terms of material choice, as it primarily relies on liquid resins [22]. Moreover, the post-production step of removing supporting structures can be time consuming and labor-intensive [22].
In the SLA classification of 3D printing, there is a 3D printing technology based on digital light processing (DLP) [23]. DLP stands out for several reasons. Its hallmark is
its unparalleled accuracy, which is manifested in the creation of models that are not only precise but also have a smooth surface finish, thanks to the light-cured resin technique it employs [23]. The computer-generated surgical guide template, a product of this technology, emerged as a beacon of innovation, offering surgeons enhanced visualization, superior treatment planning, and outcomes that could be predicted with a higher degree of certainty [24]. Its versatility is evident in its wide range of applications, from crafting presurgical dental models to aiding intricate surgical procedures [24].
On the other hand, FDM offers distinct benefits that make it a popular choice in many
applications [19]. Notably, FDM exhibits a high production speed, making it suitable for rapid prototyping and small-scale manufacturing (Figure 1b). Additionally, FDM is characterized by low startup and production costs, which makes it a cost-effective option for various industries [21]. However, FDM has certain limitations that should be considered.
One significant drawback is the poor mechanical characteristics of the printed objects,
which often exhibit reduced strength and durability [25]. Furthermore, FDM products may have a noticeable layered appearance, which can be visually unappealing. Additionally, the retained support structures in FDM prints require manual removal before the final product can be used [26].
Originally conceived for industrial design and manufacturing, the versatility and adaptability of 3D printing have seen its adoption across a multitude of sectors. The medical field has been one of the early adopters of this technology, recognizing its potential to revolutionize patient care and outcomes [12,15]. The use of 3D printing in the medical field has opened new possibilities for personalized medicine [27]. By leveraging patientspecific data often obtained through

imaging techniques such as CT or MRI scans, 3D printing can produce bespoke medical devices tailored to individual patient anatomy [28].
These include custom prosthetics and orthotics, dental implants, hearing aids, and even patient-specific surgical implants [29]. Moreover, 3D printing offers the unique advantage of producing exact replicas of patient-specific anatomical models, a feature that has profound implications for surgical planning and education [30]. Surgeons can use these models to better understand complex pathologies, practice surgical procedures, and explain treatment strategies to patients, thereby improving patient understanding and satisfaction. Despite its benefits, 3D printing in medicine is not without its challenges. Issues concerning regulatory approvals, quality control, biocompatibility of materials, and cost-effectiveness remain to be addressed. Nevertheless, the potential benefits that 3D printing brings to patient care make it an exciting area of ongoing development in medicine.

3. 3D PRINTING IN ORTHOGNATHIC AND ORAL MAXILLOFACIAL SURGERY

The integration of 3D printing technology into orthognathic and oral maxillofacial surgeries has revolutionized the medical domain [4]. This transformation has been characterized by its wide-ranging applications, from facilitating advanced preoperative planning—where specific patient models are created for detailed visualization and simulation of surgical steps—to enhancing intraoperative guidance with the help of personalized surgical guides [2]. Postoperative care has equally been transformed by 3D printing, introducing the realm of custom prosthetics and implants, which are pivotal in accelerating patient recovery and ensuring optimal rehabilitation outcomes [31]. The benefits of these 3D-printed surgical models and guides extend in various dimensions. Primarily, they provide unparalleled surgical precision tailored to each patient's unique anatomical features, ensuring predictability during surgeries [32].
Beyond the surgical process, these 3D models have shown considerable value in the sphere of patient communication. They offer a tangible and illustrative tool, facilitating a deeper understanding of the surgical process for patients and presenting an informed base for obtaining patient consent [33]. Multiple case studies echo the transformative potential of 3D printing in this surgical niche. For instance, research indicates that using 3D printed surgical guides can drastically reduce surgical time, simultaneously ensuring greater precision and thereby minimizing potential complications [34]. Another study accentuated the effectiveness of a patient-specific 3D printed implant, documenting its pivotal role in expediting postoperative recovery and optimizing aesthetic outcomes [35].
In a similar vein, the significance of 3D models in enhancing patient comprehension and subsequently obtaining informed consent was highlighted, marking a direct correlation with elevated patient satisfaction and confidence in the therapeutic approach [36]. Shifting the focus to facial reconstructions, the pioneering introduction of a customized 3D titanium implant stands out with its multifaceted applications [37]. These implants not only furnish the essential mechanical support required for the compromised area but are also marked by their biocompatibility, thus substantially minimizing risks such as rejection or adverse reactions [38].
In the realm of reconstructive efforts for maxilla and mandible defects, the success of a tailored titanium device is prominent [40]. By harnessing the power of computer-aided design and manufacturing (CAD/CAM) and amalgamating it with electron beam melting technology, a personalized implant was fashioned, mirroring the specific bone defect [31].
The application of reconstruction plates following tumor removal for the purpose of reconnecting mandibular segments has been associated with the potential complications of plate exposure and the formation of oro-cutaneous fistulas [42]. According to the research of Jo et al. [31], the mandible, a component of the human jaw, can be fitted with a custom-designed implant that incorporates a plate, which extends to tHe lingual side . The plate utilized for securing screws extended from the implant body and was adjusted to the lingual surface of the mandible [31]. By utilizing this lingual plate, it was possible to decrease the buccal volume of the implant, thereby mitigating the risk of plate exposure [31]. Furthermore, through previous mechanical tests, it was established that the EBM titanium implant exhibited sufficient strength to effectively support mandibular jaw movement and withstand bite force.
The efficacy of the customized 3D implant has been demonstrated in the successful treatment of maxillofacial bone defects [47,48]. Moreover, efforts have been made to extend its application to the repair of alveolar bone, thereby improving tooth rehabilitation outcomes [49]. In such cases, a customized titanium tray, augmented with an iliac bone graft, is employed to restore the bone defect,and facilitate tooth implantation [50]. Another noteworthy application of the implant's specific design is found in hemi-mandible reconstruction for patients with hemifacial microsomia [51]. This design incorporates vital components such as the mandibular condyle, ramus, body, and tooth prosthesis, resulting in a comprehensive and tailored solution for the specific anatomical requirements of these individuals [51].
Overall, the porous structure of the EBM implant plays a crucial role in promoting bone integration, facilitating osteogenic cell migration, and providing a successful implantation solution for various maxillofacial bone defects [41,49–51].

4. THE EMERGENCE OF VIRTUAL SURGICAL PLANNING

Virtual Surgical Planning (VSP) is a notable advancement in the field of orthognathic orofacial surgery, signifying the ongoing evolution of these surgical practices. It is an outcome of the digital revolution in healthcare, employing computer technologies, advanced imaging, and simulation software to meticulously plan

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intricate surgical procedures [52]. This innovative technique allows surgeons to visualize the operation in a virtual environment prior to its actual occurrence, thereby augmenting the predictability, precision, and customization of surgical procedures to meet the unique needs of individual patients (Figure 2).

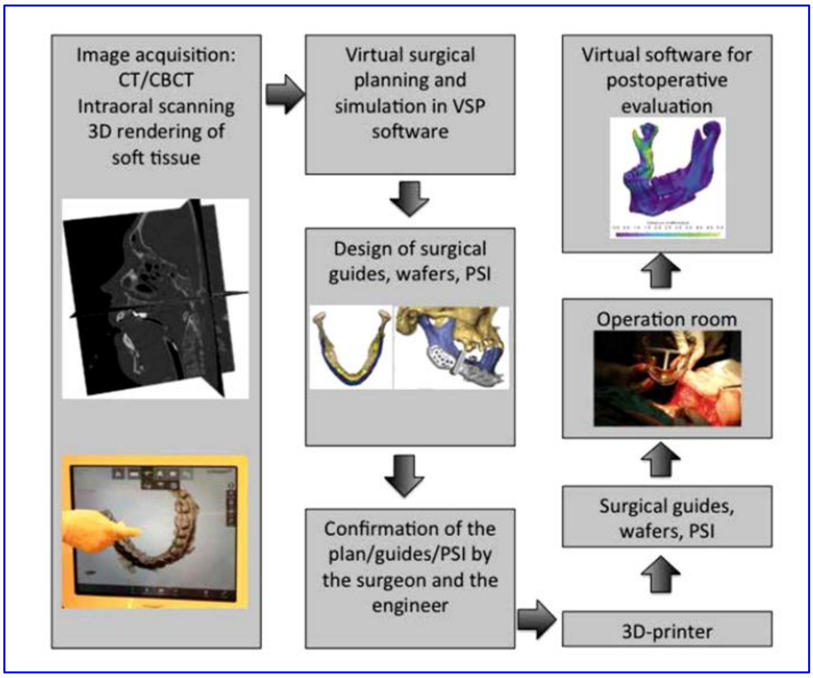

FIGURE 2- An example of a standard workflow in VSP

By utilizing VSP, surgeons can gain a comprehensive understanding of the surgical procedure before operating on the patient [53]. This ability to visualize and simulate the surgery in advance enhances the predictability of outcomes, as potential challenges and complications can be identified and addressed prior to the actual procedure [54]. This can significantly reduce the risk of unforeseen complications and allow for better planning and preparation.

Furthermore, VSP enables surgeons to achieve a higher level of precision in their surgical interventions [55].
Another significant advantage of VSP is its ability to tailor surgical procedures to the specific needs of individual patients. Each patient's anatomy and condition are unique,
and VSP allows surgeons to customize their approach based on these individual characteristics. This patient-specific tailoring can result in a more personalized and effective surgical intervention, ultimately leading to improved patient outcomes and a higher quality of care.
Traditional planning methods for orthognathic and oral maxillofacial surgeries predominantly relied on two-dimensional imaging techniques such as X-rays and hand-drawn sketches for preoperative planning [4]. This approach, although functional, was associated with several limitations including lack of spatial context, variability in interpretation, and inability to customize the procedure based on individual patient anatomy [56]. The advent of VSP has addressed these limitations, offering a three-dimensional, highly interactive, and patient-specific approach to surgical planning [52]. With VSP, surgeons can manipulate 3D models of a patient's anatomy, plan the surgical approach, anticipate potential challenges, and even rehearse the procedure, all before the patient is on the operating table [57].
This shift towards virtual techniques not only facilitates better surgical outcomes but also improves efficiency, reduces surgical risk, and enhances patient satisfaction by allowing for a clear preoperative dialogue [15]. The use of these techniques represents a new era in orthognathic and oral maxillofacial surgery, one characterized by technological integration, precision, and individualized patient care.

5. VIRTUAL SURGICAL PLANNING IN ORTHOGNATHIC AND ORAL MAXILLOFACIAL SURGERY
The application begins with the acquisition of patient-specific imaging data, typically through CT or CBCT scans, which are then converted into 3D digital models (Figure 4).

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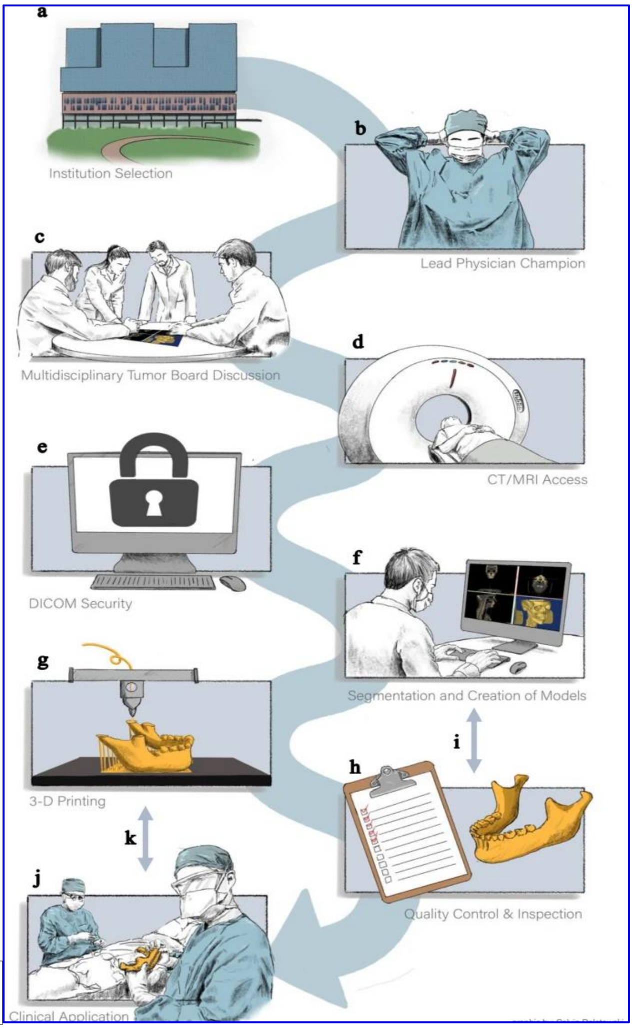

FIGURE 3 -(a) Identify an institution that has the proper imaging equipment to support a self-sufficient 3-D printing lab; (b) Recruit a lead physician (surgeon, radiologist, etc.) (c) Utilize tumor board, trauma cases, and other clinical scenarios that identify a wide range of patients who could benefit from 3-D models; (d) Ensure proper cross-sectional imaging (CT/MRI) Digital Imaging and Communications in Medicine (DICOM) access; (e) Ensure DICOM storage for selected patients remaining under the institution's HIPAA-protected firewall; (f) Team manipulates each patient's specific imaging and creates 3-D Computer-Aided Design (CAD); (g) Final CAD model print execution per clinical requirements; (h) Quality control for proper sterilization and model preparation for clinical use in the operating room; (i) Feedback loop between Quality Control & Inspection and Segmentation and Creation of Models to improve future prints; (j) Deliver the model for clinical application per institutional requirements; and (k) Feedback loop between Clinical Application and 3-D Printing to improve future prints.

These models can be manipulated to simulate various surgical outcomes and to design patient-specific surgical guides [6]. It allows the surgical team to visualize complex anatomical structures, understand the spatial relationships better, and perform virtual osteotomies and repositioning, thus fine-tuning the surgical plan [21].
Several case studies have underscored the effectiveness of VSP. In a study conducted
by Chen et al. [58], the use of VSP in orthognathic surgery resulted in a significant reduction in operative time and an improved postoperative outcome in terms of facial symmetry and patient satisfaction. Another study by Valls-Ontañón et al. [59] demonstrated improved accuracy in executing the surgical plan using VSP, resulting in better postoperative occlusal outcomes. These cases underscore the increasing role of VSP as an integral part of surgical planning in orthognathic and oral maxillofacial surgery.
In order to achieve precise mandibular ostectomy through an intraoral approach, the utilization of a 3D-printed surgical guide has proven effective [60]. Despite limited visibility during the surgery, the surgeon can accurately identify the osteotomy site with the assistance of the surgical guide [61]. This guide is prepared preoperatively by adapting it to a 3D digital model [62]. Numerous variations of 3D-printed surgical guides or templates have been successfully employed in mandibular contouring surgeries, demonstrating their suitability for surgical purposes [61]. When performing a

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mandibular ostectomy, adherence to the computer-assisted simulation planning (CASP) is crucial, ensuring proper transfer of the preoperative surgical template [63].
The use of CASP and a 3D-printed surgical guide in mandibular contouring surgery offers advantages over traditional planning techniques relying on 2D images [64,65]. By incorporating CASP and the surgical guide, operating time can be reduced and surgical accuracy increased [66]

6. THE SYMBIOSIS BETWEEN 3D PRINTING AND VIRTUAL SURGICAL PLANNING

A pivotal advancement in orthognathic and oral maxillofacial surgery is the amalgamation of 3D printing and VSP [67]. This combination serves to revolutionize surgical planning and implementation by providing tactile 3D models for visualization and planning, and accurately designed surgical guides for execution (Figure 4).

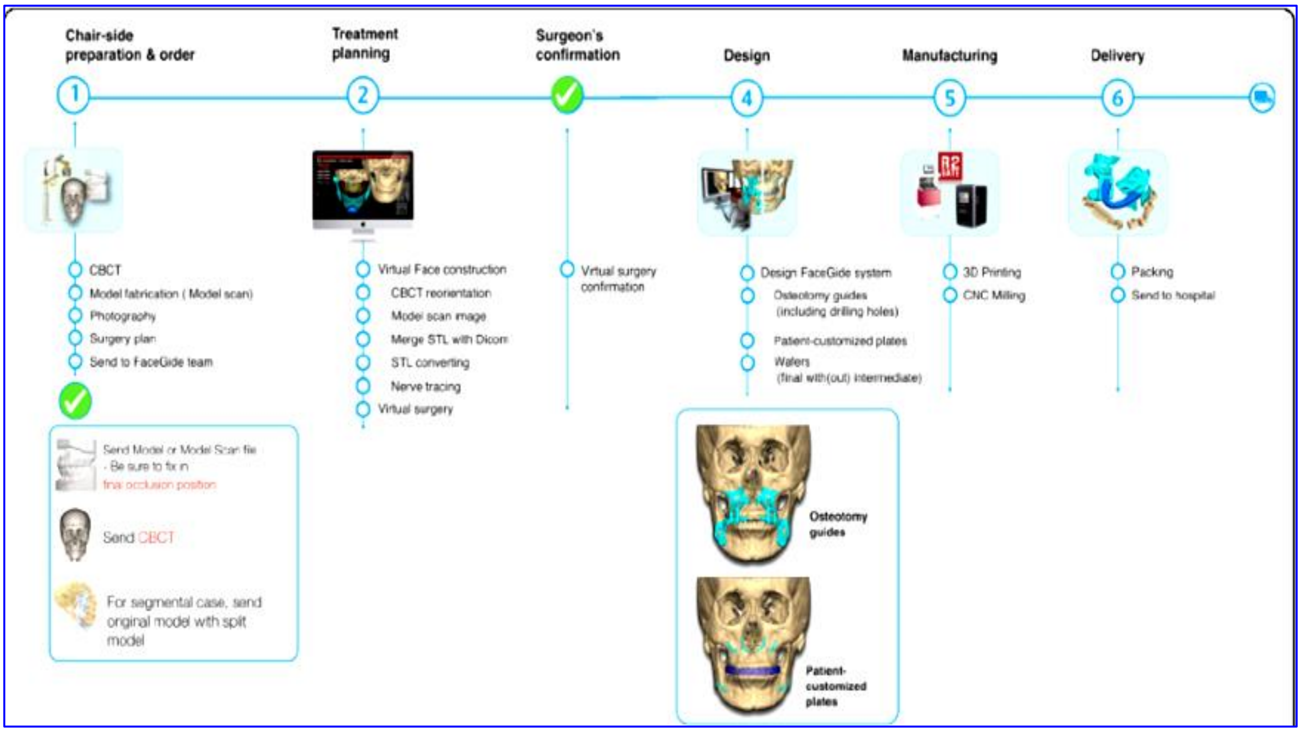

FIGURE 4 - Symbiosis between 3D Printing and Virtual Surgical Planning

The virtual environment allows for a meticulous preoperative plan, while 3D printing translates this plan into a tangible reality, serving as a road map during surgery. The marriage of 3D printing and VSP creates a symbiotic relationship that enhances surgical precision, reduces operative time, and improves patient-specific outcomes [68].

7. CHALLENGES AND FUTURE DIRECTIONS

Despite the immense potential of 3D printing and VSP in orthognathic and oral maxillofacial surgery, these technologies are not without their limitations. One of the major challenges in adopting these technologies is the need for extensive software training [71].
Professionals need to acquire the necessary skills to operate the software used for designing and creating 3D printed models and surgical guides [72]. This training can be time consuming and may require additional financial resources. Moreover, the software itself may have a steep learning curve, especially for those who are not familiar with CAD programs [73].
Financial constraints can also impede the widespread adoption of these technologies. The cost of acquiring and maintaining the necessary equipment and software can be significant [74]. Additionally, the materials used for 3D printing, such as biocompatible resins, can be expensive [75]. These financial considerations may limit the accessibility of these technologies to some healthcare institutions or individual practitioners. Another limitation is the reliance on high-quality digital imaging for accurate 3D printing and surgical planning [76]. The accuracy of the printed models and surgical guides depends on the quality of the initial digital scans [72]. Patient-related factors, such as movement during imaging or dental prosthetics, can affect the accuracy of the digital models [77]. Technical factors, such as image resolution and artifact interference, can also impact the quality of the digital scans [78]. Therefore, careful attention must be given to the imaging process to ensure accurate representation of the patient's anatomy.

Furthermore, the rapid advancement and adoption of 3D printing and VSP have outpaced the development of regulations and standards. As a result, there are concerns
about patient safety and procedural accountability [79]. It is crucial to establish guidelines and regulations to ensure the quality and reliability of these technologies. This includes standardized protocols for imaging, software validation, and quality-control measures for 3D printing and surgical planning processes. In the context of materials used in 3D printing for medical applications, especially in oral and maxillofacial surgery, a narrative review highlighted the use of materials such as hydroxyapatite, tricalcium phosphate, bicalcium phosphate, apatite–wollastonite glass ceramics, stem cells, and collagen [80]. The review emphasized the need for further research on the modeling, efficacy, and safety of these natural materials to ensure their suitability and safety in surgical applications [80].According to the Regulation (EU) 2017/745 of the European Parliament and of the Council dated 5 April 2017, all 3D-printed products are classified as custommade devices [81]. As per this regulation, manufacturers of such custom-made devices are required to adhere to conformity assessment procedures in order to ensure compliance with safety and performance requirements [82].
Looking ahead, continued technological evolution is likely to further refine the precision, affordability, and accessibility of 3D printing and VSP in orthognathic and oral maxillofacial surgery. Integration of artificial intelligence and machine learning could automate aspects of surgical planning, making these technologies more user-friendly and efficient. Moreover, advances in biomaterials may lead to the production of bioresorbable or tissue-engineered 3D-printed implants, fostering innovation in patient-specific treatment.

8. CONCLUSIONS

Traditional methods in orthognathic and oral maxillofacial surgery come with inherent risks and complications such as infection, bleeding, nerve damage, issues with wound healing, unfavorable bone segment movement, and relapse. These methods rely heavily on the surgeon's skill and experience for precision, which can lead to variability in outcomes. Translating two-dimensional pre-surgical plans into three-dimensional surgical procedures can be challenging and may affect the accuracy of the operation.
As medicine moves towards patient-centric care, the demand for personalized surgical
methods increases. Surgeons need to tailor surgical plans to the individual patient's anatomy and desired outcomes. The need for greater surgical precision and predictable outcomes is paramount in improving patient satisfaction rates and reducing complications.
The amalgamation of 3D printing and VSP serves to revolutionize surgical planning and implementation by providing tactile 3D models for visualization and planning, and accurately designed surgical guides for execution. The virtual environment allows for a meticulous preoperative plan, while 3D printing translates this plan into a tangible reality, serving as a roadmap during surgery. This convergence of digital planning and physical modeling facilitates a more predictable, personalized, and precise surgical process, paving the way for advanced patient care in orthognathic and oral maxillofacial surgery.
Professionals need to acquire the necessary skills to operate the software used for designing and creating 3D-printed models and surgical guides. This training can be time consuming and may require additional financial resources. Moreover, the software itself may have a steep learning curve, especially for those who are not familiar with CAD programs.

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