INVITED REVIEW

A review on computer-aided design and manufacturing of patient-specific maxillofacial implants

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ABSTRACT

Introduction: Various prefabricated maxillofacial implants are used in the clinical routine for the surgical treatment of patients. In addition to these prefabricated implants, customized CAD/CAM implants become increasingly important for a more precise replacement of damaged anatomical structures. This paper reviews the design and manufacturing of patient-specific implants for the maxillofacial area.

Areas covered: The contribution of this publication is to give a state-of-the-art overview in the usage of customized facial implants. Moreover, it provides future perspectives, including 3D printing technologies, for the manufacturing of patient-individual facial implants that are based on patient's data acquisitions, like Computed Tomography (CT) or Magnetic Resonance Imaging (MRI).

Expert opinion: The main target of this review is to present various designing software and 3D manufacturing technologies that have been applied to fabricate facial implants. In doing so, different CAD designing software's are discussed, which are based on various methods and have been implemented and evaluated by researchers. Finally, recent 3D printing technologies that have been applied to manufacture patient-individual implants will be introduced and discussed.

ARTICLE HISTORY

Received 30 October 2019
Accepted 25 February 2020

KEYWORDS

Computer-Aided design; implant; patient-specific; maxillofacial; 3D Printing

1. Introduction

The significance of designing a medical implant for a mandible prosthesis, directly affects the personal satisfaction of patients with serious stages of temporomandibular ankyloses. However, the outcome of every implant is different according to a patient's condition. A person who has endured an extreme injury – that presents an unforeseen variation from the norm – can benefit from a prosthesis, which is precisely planned and customized for the patient anatomy. Additionally, the high costs of the commercially outsourced implant production could be reduced, if using in-house additive manufacturing. Hence, making a valuable prosthesis, which is biocompatible and generally reasonable, would be a significant step forward in our health system.

The temporomandibular joint (TMJ) connecting the mandibular condyle and glenoid fossa is the synovial articulation of the temporal bone. Prosthetic total joint replacement is a medical procedure, which is a last stage surgery for severe degenerative ailment of the temporomandibular joint, including ankyloses, osteoarthritis, serious condylar resorption, cancer and trauma, and is utilized when conservative therapies are ineffective [1]. The main reason for total joint replacement operation of the TMJ is to decrease the soreness and increase jaw function, maximize intra-incisal opening and improve the quality of life for the patient [2]. A significant number of intra-articular temporomandibular pathologies, for example end-stage TMJ osteoarthritis,

TMJ ankyloses, severe idiopathic condylar resorption, comminuted condylar fracture and some TMJ tumors, require removing the joint, and hence also require a joint recreation to reestablish the anatomic structure and capacity [3,4].

Precise reproduction of the mandible after a resection is essential to retain the anatomical structure of the patients' jaws, and the restoration of the facial appearance and oral cavity function can greatly improve the patients' quality of life [5,6]. This kind of anatomy reconstruction is in general regularly performed on patients with malignancies or who are in poor physical conditions [7]. Further, for patients with soft tissue defects of the oral cavity [8,9].

2. Preoperative planning

2.1. Data acquisition and medical image processing

Common utilized strategies for getting information of the inside of a patient's body are Computed Tomography (CT) and Magnetic Resonance Imaging (MRI) acquisitions. Both imaging strategies give cross-sectional images of the human body. The principal distinction is that a CT scanner uses radiation in the image acquisition process, while the MRI technique uses a magnetic field. Thereby, the quality of acquired image data relies on the accuracy of the imaging machine and the resolution of the data (voxels). Reducing the scanning

Article highlights

- The 3D printing technology has been widely used for patient-specific facial implant manufacturing, because it has the capability of fabricating very complex structures.
- Accuracy and surface finish of the implant can be enhanced by upgrading the software at the cost of time consumption.
- Researchers are working to simplify the design and manufacturing workflow of porous facial implants with user-friendly software in the future.

distance, for example, can increase the resolution. A longer scanning time can also increase the resolution, but must be trade-off against the increased radiation exposure (CT), devices usage and the condition of the patient [9]. Finally, spiral computed tomography techniques enable faster scanning compared to previous scanner generations and are nowadays standard in most modern clinical centers [10].

With the improvement of medical imaging systems and therefore higher image resolution acquisitions, the requirement for digital image processing also increases. In addition, the digital image processing is the technique for image recovery to prepare information of machine observation such as, extracting and recreation of images from CT scan data [11,12].

The usage of the image processing techniques has seen its place in often unrelated applications, because they require the same underlying technology [13]. In medicine, image processing techniques have been used for assisting in treatment decision and research [14].

Different procedures for image enhancement and image recreation are utilized. Image examination procedures including morphological image analysis, edge identification, image feature extraction, image division and shape investigation are already famous in the field of medicine. Further, much research has already been conducted to transform the 2D image slices into 3D image visualizations and volume renderings. Automatic image detection algorithms of some particular anatomical structures and pathologies usually relies on specific image acquisitions methods such as MRI or electromagnetic waves methods [15].

Surgical modeling software enables an interface to three dimensional computed tomography data with a computer-aided design or rapid prototyping (RP) framework to virtually (re-)create anatomical structures. A 3D remaking of the patient's anatomy for the geometry of the implant design, for example a bone tumor surgical procedure, requires isolating the slices of the anatomical bone structure from the CT scan data.

Byrne et al. [16] used thresholding for the segmentation of CT data in the Materialize Interactive Medical Image Control System (MIMICS) software (Materialize, NV, Belgium) to extract the 3D image of the patient skull. After the modification of a CAD based 3D model of the bone geometry, the data was matched with the original CT data to figuring out the programming for the manufacturing process.

2.2. Design of prostheses

Computer-aided design of maxillofacial prosthesis is still under development for clinical applications due to technical challenges. Various studies have been conducted through the combination of 3D scanning, computer-aided design and Additive Manufacturing (AM) [17]. By their nature, customized prostheses are unique, patient-specific devices that cannot benefit from batch or mass manufacture, like miniplates [18] or some dental splints [19]. Ackland et al. [2], for example, designed a modified Melbourne reconstructed prosthetic to match the patient's native jaw structure. CT scan data of the patient's head were required with a slice thickness of 0.75 mm (SIEMENS, Munich, Germany). Afterward, the digital images were used to generate 3D geometries of the patient's mandible and glenoid fossa (Amira, EFI, Houston, USA).

Kozakiewicz et al. [20] designed a CAD model of solid tissue using CT data, which has the thickness of the scanned slices ranged between 0.6 mm to 1.0 mm, however, the volume of engrossment included the entire mandible to the temporal bone and midface. Computer-aided design was performed using MIMICS software (Materialize, Leuven, Belgium), which is also suitable for the segmentation. Further, GeoMagic (Geomagic Corp, USA) was used to validate the standards of the implant surface and any fault/pseudo foramina were modified using the tool Geo-Magic Studio 14 and SolidWorks (Dassault Systemes SolidWorks Corp, USA) in the structure design of the bone socket and condylar implant using the mirror technique. After the successful design, the 3D surface of the bones was obtained and exported as a 3ds file. Figure 1(a) shows a virtual model of a modified prosthesis created using a computer-aided designing software. Figure 1(b) shows a computer-aided design of the ramus and condyle implant model [20].

Surgical data processing is needed to produce an output file format acceptable for 3D printing, such as .STL file. The Radiological Society of North America (RSNA) 3D printing Special Interest Group (SIG) concurs with the FDA that the software that has been favorably evaluated used to translate medical images into 3D printed acceptable file formats from all aspects of patient care, defined by the SIG as all interactions with healthcare professionals, or patients and their families related to medical field [21].

The finite element analysis method (FEA) is usually a powerful tool to show the biomechanical properties of a difficult geometry [22,23]. Koriath et al. considered a peripheral impact on the biomechanics of the mandible, especially with respect to condyles [24]. Most experts agree that the method provides an exact arrangement of the cranial fault recover operation and the implants are admissible with high assessments, bio-compatibility and mechanical properties [25–27].

However, conventional CAD techniques using common software, like UniGraphics (UG) (Siemens PLM programming, Plano, USA), Solidworks (Dassault Systems Solidworks Hill, USA), Magic RP and 3-Matic (Materialize, Leuven, Belgium), Geomagic (3-D SYSTEMS, Rock Hill, USA) are tedious and complicated. Jardini et al. described a workflow to design and develop a bio-model and modified implant for the surgical recreating of a large cranial flaw using some commercially

Figure 1. Virtual model of the modified implant created using a CAD program (a). Computer-aided design of the ramus and condyle model (b) [20].

available software's, for example, Solid Works, Magics, and MIMICS [28].

The initial step in customizing these devices for the bone anatomy of the individual patient is to perform a CT scan that accurately shows the geometry of the patient's existing bone structure. The OMX solutions production engineers used the Materialize Mimics software to convert the CT scan to a digital model of the patient's bone and then used Materialize 3-Matic software to design the implant to match the patient's 3D skeletal anatomy [29].

In designing of custom implants, OMX solutions production engineers must guarantee that the whole assembly, including bone attachments and implant components will not fail. Without simulation, it is important to print each implant and conduct a physical test on them. If it did not pass this test, it is important to redesign, remanufacture and modify, which is costly in terms of time and money. However, conducting the physical test on the whole assembly for every patient is currently not possible.

Hsu et al. designed a TMJ from the mandible of a human male using his CT data [30]. The prostheses have 11 screw openings and were situated on the right side of the mandible ramus (Figure 2(a)). The interface between the stem of the prosthesis and the cancellous bone was displayed with the surface-to-surface contact components with a friction coefficient of 0.42 [31].

Another fossa was designed by Zou et al. that needs to fill up the space in a remnant fossa, so the requirement for a bone graft was avoided. The Chinese standard mandible ramus prosthesis point type was selected according to the CT measurement of the condyle-ramus angle (Figure 2(b)) [32].

2.3. Design of porous

The porosity can be explained as the rate of void space in a solid part [33]. The gravimetric method as shown in the Equation (1), is used to measure the porosity P .

$$P = (1 - \rho_{\text{structure}} / \rho_{\text{material}}) \times 100\% \quad (1)$$

Where $\rho_{\text{structural}}$ is the porous structure density and ρ_{material} is the bulk alloy density, and it can be calculated by the mass of the structure (m) divided by its volume (V) [34].

Bone is an open cell porous material laid down by osteoblast cells and characterized into two categories: (1) Compact bone and (2) cancellous bone. The previous external shell of the bone was hard with lower porosity [35], and the next bone has a higher porosity cell structure, which is higher in weight and more fragile than an external shell of the bone. The porosity of the bone increases from 30% to 95% and the pore size reaches from 200 to 1000 μm [36–38]. Medical devices and implants with an elevated level of porous have gained interest because of their notable biocompatibility,

Figure 2. Solid model of the mandible and the implant (a), Chinese standard TMJ Implant Prostheses (b).

which is valuable for bone registration and manufacturing, and as a basic component of bone ingrowth of metal implants [39,40]. Kuboki et al. [41] examined the osteogenesis prompted by one morphogenetic protein utilizing with both strong and permeable particles in rats. The result proved that the osteogenesis just happens in porous structures [35,41].

The scaffold shape and inner pore design can be characterized by utilizing the image based design (IBD) process [42]. In this technique, a picture of the joint to be reproduced is gotten by MRI as well as CT. The tissue substitution domain is distinguished by data handling and digitization; this makes the outside scaffold structure. The heterogeneous interior scaffold design would then have the capacity to be made. The porous design can be made to utilize structures like regular mesh three-dimensional structures, diamond structure, and tetrahedral structure. Some examples of porous structures are shown in Figure 3, by utilizing microstructure topology advanced techniques [43]. The outer scaffold structure is then assembled with the designer database to make the end shape of the scaffold as a picture database. The inner scaffold structure can then be shaped and analyzed. Finally, the total scaffold structure is then converted from picture information to a STL file for manufacturing using Solid Freeform Fabrication (SFF). With this system, a biomimetic scaffold containing an orthogonal porous region was planned and created from a polymeric material by means of SFF [44].

However, the solid structure of the sheet shows only mechanical performance, whereas detached porous structures have serious disadvantages. The interconnectivity of the pore is good for scaffold structure because it supports the fluid transport inside the body, help vascularization, cell activities and tissue in growth [31,45]. Solid sheet gyroid shows a discontinuous pores structure, thus it is not preferred by experts in the field of tissue engineering. As compared with solid sheet structures, a solid network gyroid design structure provides a good mechanical property. Moreover, the volume fraction is controllable because pores are interconnected and the structure is more reliable and practical for an orthopedic implant. Moiduddin et al. presented a system for model design and simulation of a modified porous plate [46].

Schek et al. [47] utilized a scaffold with a smaller complex structure for the assessment in vivo of how the scaffold

structure and material properties affect the tissue manufacturing. These composite frameworks were made out of two chambers, one hydroxyapatite (HA) and another one Poly-L-lactic destructive [PLA, MW = 147000; Birmingham Polymers, Inc., Birmingham, AL, USA]. The setup of each is 3 mm height and 5 mm diameter. The HA phase contained either 300 μm dia orthogonal pores with a porosity of 50 percent. These were created utilizing an informal SFF procedure [48]. These computers based molds were made with model creator II (Solid shape, Inc. Merrimack, NH, USA) wax inkjet printer and an HA/acrylic slurry was manufactured into the shape and sintered [49]. The polymer wipes were made through a salt filtering strategy [30]. Sieved NaCl (100–120 μm dia; Sigma, St Louis, MO USA) were pressed into 5 mm dia by 3 mm high shape and 70 μl of 7.5% w/v PLA in methylene chloride (Sigma) and hurled into the molds. As a result, the dissolvable has vanished and the said porogen expelled by splashing water for 48 hours.

Mechanical properties of Triply Periodic Minimal Surface (TPMS) were utilized to develop a metallic TPMS structure with powder bed combustion manufacturing methods (SLM, EBM and SLS) especially for the titanium and its composites [49–53].

A porous mandible was designed with GE Light-speed (GE Healthcare, Chicago, IL, USA) CT with 120 kVp for a 63-year-old patient. The CT scanning was performed horizontally with a layer thickness of 1.25 mm and the total number of layers was 203. The 3D part of the life structure was subdivided utilizing OsiriX (1.7.5, Pixmeo, SARI, Geneva, Switzerland) with 20 smoothing cycles, 0.5 decimate and 500 HU density. Finally, the mandible was placed to its intended position. According to the result of the surgeon, the computer-aided design of the implant was performed by utilizing 3-Data Expert (11.0, DeskArtes, Helsinki, Finland) and VisCam RP (3.6, Marcam Engineering, Bremen, Germany) as shown in Figure 4 [54].

3. Manufacturing of prostheses

After completing the prosthesis design, the manufacturing process is the next major step for creating a 3D part [55]. There are some traditional mechanical technologies for fabricating uniform prosthesis. For example, with Computer

Figure 3. Various structures of scaffold.

Figure 4. Patient-specific rendered mandible model (maroon) attached to its implant (white).

Numerical Control (CNC), fabrication of metal prosthesis by cutting should be proceeded by serious verification of a part program [48,56]. Another stock prosthesis was manufactured by a researcher [57], which requires minor mechanical modification before fixation. The advantage of stock prostheses is being relatively economical when compared to custom prostheses.

In addition, Additive Manufacturing (AM) methods are nowadays mostly used for the fabrication of modified patient-specific implants. As indicated by some researchers [58], these items could boost the results of artificial TMJ restoration.

Numerous literature has indicated that AM of titanium made scaffolds can be utilized to fix bone damages since it has relative good biomechanical properties [59]. Few researchers designed and manufactured a modified titanium condyle via Selective Laser Melting (SLM) in 2014 [60]. They designed a hollow condyle part by using two titanium alloy plates to fit the prosthesis on to the external surface of the remaining mandible. A methodology of manufacturing the inward structure and association plan of the condyle segment that varies from the current investigation. Taking current outcomes into account, this system might be appropriate for the manufacturing of novel TMJ Prosthesis.

Furthermore, the benefit of AM technology is that different parts with different capacities can be manufactured simultaneously with better characteristics being adjustable to justify a variety of engineering requirements. Selective Laser Melting (SLM) 3D printing innovations can be used to manufacture irregular and complex shapes. The purpose behind improving scaffold fabrication is to overcome biological constraints and diminish the pressure protecting impact and weight of the prosthesis.

There are still numerous ways to fabricate implants, for example, Rapid Prototyping (RP) Technology, Hybrid techniques with CNC and High precision machining [61], hybrid lithography, Selective Laser Sintering (SLS) and Electron

Beam Melting (EBM). The RP technology approach contains a group of novel strategies generally used in engineering for the fast manufacturing of geometrically complex ideal and functional solid models [55].

Zheng et al. performed in 2019 an analysis of tumor resections in Mimics software according to common standards. A 5 axis milling machine (DMU60; DMG Mori, Bielefeld, Germany) was used to develop fossa component from ultra-high molecular weight polyethylene. The 3D printing machine (Arcam A1, Molndal, Sweden) was utilized to manufacture the titanium (Ti6Al4V) ramus and skull base parts. All components were polished and the surface finished subjected to sandblasting treatment. The precision and stability of the implants were then checked by fitting the combined prosthesis into a 3D printed skull model (Figure 5(a)). After the successful fixation, the 3D model was imported in MIMICS and converted into a 3D file supported format such as .STL (Figure 5(b)) [62,63].

Zheng et al. [63] compared two kinds of TMJ prostheses commercially available for surgical operations: (1.) Zimmer Biomet products (stored or customized) (Biomet micro-fixation, Jackson vile, FL, USA) and (2.) Fully customized TMJ products (TMJ Concepts Inc., Camarillo, CA, USA) (Figure 6(a,b)) [64].

In addition, there is a unique TMJ medical procedure requirement for the innovative work of Chinese TMJ prosthesis. According to previous studies, the specialists have planned a modified TMJ prosthesis (Figure 6(c)), which is entirely different from the commercially available Zimmer Biomet and TMJ prosthesis [65]. Table 1 shows manufacturing technologies in the field of implant manufacturing their advantages and disadvantages used by many authors.

4. Clinical applications

After the discussion of various technologies for the designing and manufacturing of customized facial implants, we present an overview of operations that have conducted in hospitals for implant placement. Many patients have been treated with different kind of facial implant surgeries. I doing so, every patient underwent an own specific surgery and received a special material manufactured implant. Some clinical verifications are discussed here to show that the 3D printed customized implants have been successfully placed into patients.

Zheng et al. introduced a clinical study of customized designed and 3D printed prostheses of TMJ in 2019. Patients with one-sided end-stage TMJ osteoarthritis have been enlisted from November 2016 to March 2017. CT scans were performed for every patient and then used to generate a 3D recreation model. The modified TMJ prostheses were comprised of three segments including the condylar head, fossa and mandibular handle units, which were planned based on the patients anatomy, and were manufactured using the 3D printing technology. The entire condyle (Figure 7(a)) and the lower part of the articular eminence (Figure 7(b)) were osteomized and guided by surgical templates via holes and planes [66]. Firstly, the parts of the fossa were fitted with titanium screws (Stryker Fixation System, Kalamazoo, USA) according to the holes of the templates (Figure 7(c)).

The condylar head parts with mandible handle encouraged the addition of titanium screws with the designed holes in the

Figure 5. Titanium condylar prostheses (a). Combined prosthesis product by 3D printing technology (b).

Figure 6. The difference between the Zimmer Biomet or TMJ prosthesis and new prosthesis: The Zimmer Biomet prosthesis (a). Prosthesis with a TMJ concept (b). Researcher based TMJ prosthesis (c) [29].

template. At that point the lower resultant holes of the mandible parts were fixed with the screws by the support of an endoscope and trans-buccal reactor (inserted through a 3 mm incision in the parotid-masseteric region) and the occlusion was deemed as stable as preoperative as shown in Figure 7(d,e). After the condylar head components insertion, a part of fat graft was placed around the condylar head part to obliterate the resultant space to ignore the development of the heterotopic bone on the prosthesis (Figure 7(f)) [57,67,68].

Another clinical experiment was conducted for the reconstruction of the TMJ by a senior surgeon [69]. First of all, the temporomandibular joint, the mandibular ramus and the angle were exposed. Then, customized 3D-printed cutting guides and fossa templates were used for accurate condylar resection and best prosthesis fitting. During the surgery, the occlusion was secured and fixed using trans gingival screws, and the wound was finally closed after the fixation of the fossa and condyle components with titanium screws (Figure 8).

A 58-years old woman with a graphically confirmed diagnosis of osteoarthritis symptomatic of the left joint was enrolled. The patient fulfilled the National Institute of Health and Chronic Clinical Excellence guidelines for TMJ replacement and

experienced chronic jaw had sore and small range of jaw joint motion and had no previous surgery or neurological conditions. The cadaveric examples embedded with the Melbourne prosthetic TMJ were afterward tested with passively jaw movement without observable TMJ subluxation. Visual survey of the prosthetic TMJ revealed the condylar head to remain perfect in the fossa during passive maximal jaw opening, shutting medical lateral and foremost back movement. Figure 9 showing fossa and prosthetic condylar segment, front fossa flange, fixing screws, and mandibular ramus [71].

An entry point with a temporary enlargement and a post mandibular or submandibular approach was used in [71] to reveal the common bone, zygomatic curve, joint case and mandibular ramus. The storage trunk of the facial nerve was distinguished and protected, however, if the sore was excessively huge, the facial nerve was cut and sutured again during a restorative technique. The resection method arrangement was as follows: (1) the condyle was osteotomized at the component of the lower edge of the damage, essentially over the mandibular foramen attempting to shield the second rate alveolar group; (2) an advanced osteotomy template was used to execute the zygomatic curve osteotomy; (3)

Table 1. 3D manufacturing technologies with advantages and disadvantages.

Author	Technology	Pros	Cons
Kozakiewicz W et al. [20] Akmal J et al. [58] Hoffmann B [59] Zheng JS et al. [64] Lerry M et al. [65] Zheng JS et al. [69] Shilo D et al. [80]	3D Printing	<ul style="list-style-type: none"> • Good accuracy • Faster Production • Lower Risk • Freeform of creating complex shapes • Practical product testing 	<ul style="list-style-type: none"> • Infringement of copyright • The price is very high
Chehule CL et al. [49] Ataee A et al. [50] Yanez A et al. [51] Fink S et al. [55]	Selective Laser Melting	<ul style="list-style-type: none"> • Lower cost • Shorter assembly time • High mechanical load capacity 	<ul style="list-style-type: none"> • Rough surface on some materials • Thermal distortion on polymer parts
Wicher J et al. [60] Chehule CL et al. [49] Ataee A et al. [50] Yanez A et al. [51] Fink S et al. [55]	Selective Laser Sintering	<ul style="list-style-type: none"> • Can fabricate porous prototypes • Variety of materials • 60% density of modeled parts 	<ul style="list-style-type: none"> • Rough surface finish
Chehule CL et al. [49] Ataee A et al. [50] Yanez A et al. [51]	Electron Beam Melting	<ul style="list-style-type: none"> • Higher density about 99% • Multiple parts can be manufactured • Unused powder can be recovered and reused 	<ul style="list-style-type: none"> • Limited availability of materials • The process is very expensive • Rough surface finish

Figure 7. The medical application for a new TMJ prosthesis. The recreation of the whole condyle and the lower portion of the articular distinction by utilizing the medical template (a, b). The fitting of the fossa segment with the designed holes in the templates (c). The mandibular handle component fitting with the support of an endoscope and a trans-buccal retractor (d, e). The graft-free fat collected from the buccal fat cushion to fill the holes around the prosthesis neck (f).

a temporal craniotomy was accomplished over the unmatched edge of the tumor, as set apart by the computerized layout, by surgical separating the dura to the dimension of the foramen oval and withdrawing the temporal lobe; (4) the foremost and back osteotomies were guided by the advanced formats depending on the preoperative plan; (5) the mass was moved to the original position by removing medial and posterior equipment (Figure 10(a)). If the mass was mammoth and

accommodating subject to an intraoperative biopsy, it could be osteotomized normally and removed part by part. Thinking about the essential standards of an extended joint substitution [71–73] the consolidated prosthesis, temporal bone, as well as zygomatic curve were embedded and fitted with titanium sheet and screws (Stryker Fixation System, Kalamazoo, MI, USA) in perspective of the past occlusal relationship and the organizing condition between the prosthesis and the surface

Figure 8. Intraoperative view of an inserted left-sided total joint prosthesis [70].

bone (Figure 10(b)). Fat reaped from the buccal fat cushion (a few parts), just as under the skin in the pre-auricular or submandibular territories, was folded over the condylar head. Then the surgical aspect of the skull base segment to devastate the

subsequent dead space following the resection and to anticipate the development of heterotopic bone around the prosthesis, in addition to the meningeal simulation. The impediment was rechecked and then the injury was closed in layers with 18-gauge drains [74,75].

5. Conclusion

Many 3D designing software companies are struggling to provide better accuracy in designing surgical implants. The advancement of image processing and 3D printing innovation is opening up numerous doors for medical applications and the manufacturing of custom implants. The advanced high-quality medical imaging data can further be processed to generate 3D images that are necessary for 3D printing of physical objects. It has been reported useful for manufacturing 3D physical models of an implant.

The demand for 3D printing is increasing and will become more pervasive in surgical usage in the near future as the doctors and engineers are increasingly utilizing the technology's flexibility in the production of medical items. In addition, after implant models have been created virtually, the osteosynthesis can be designed virtually on these models, which can then be produced without tension [76,77]. Furthermore, researchers and scientists are working to make Artificial

Figure 9. Melbourne prosthetic TMJ cadaveric specimen after replacement [71].

Figure 10. The operation preview: Total resection of injury (a) and consolidated prosthesis implantation (b).

Intelligence (AI) user-friendly in the future for automatic implant manufacturing [78]. It will help surgeons, and implant manufacturers to design and manufacture the prostheses with a good surface finish, better accuracy in less time. Finally, virtual reality (VR) [79,80] can allow an immersive pre-operative implant visualization and augmented reality (AR) [81] can support the positioning of facial implants during an intervention.

6. Expert opinion

The additive manufacturing technique has the benefit of producing objects with a free-form structure, which is not possible with conventional manufacturing techniques, particularly in facial implant manufacturing. The 3D printing systems can make models that give a useful comprehension of the unusual life structures and pathology of patients. Additionally, it can help to increase the knowledge in learning the manufacturing of facial implant but can also help to create modified implants that are customized to medical requirements. The 3D printing innovation has been considered to be helpful in patient-specific orthopedics, for example, in the formation of an anatomical model of the mandible for the TMJ, education, patient-specific instruments and modified 3D manufactured implants.

Only a couple of researchers have recently surveyed the 3D manufacturing technology and its applications in the manufacturing of facial implants [75,76,80,82,83]. However, they were accounted for the most part from the perspectives of radiologist, specialists, and engineers. The procedure to turn digital images into a physical 3D item has been explained in a literature review article [76]. The overall chain contains three principal stages: 1. Image acquisition, 2. Image post-processing and 3. 3D manufacturing.

Standard bone implants are usually manufactured using subtractive fabrication techniques and they meet the restorative necessities for most patients based on their own medical images. Post-tumor implants manufactured by 3D printing may be the ideal reconstructive arrangement as they can be altering to encourage different conditions of the bone deformities after tumor resection. Early studies have recommended that the modified implants were profitable for reconstruction in scapular, clavicular or pelvic bone tumors, which have a special bone arrangement and no open off the rack prosthesis [84,85]. Additionally, pre-fabricated modified implants and 3D models empowered specialists to observe a better plan for medical procedures before the real surgery. To accomplish the best fit of customized implants, specialists may require controlling instruments as PSI [86] or computer navigation [87] to duplicate the comparative resection plane as planned per planning software.

With the advances in CAD and 3D printing, biomedical specialists and implant factory owners can incorporate the entire designing procedure from 3D image information over modified implant manufacturing to a close collaboration with doctors. To propagate the prominence of 3D printing technology among specialists, a coordinated system of computers should be developed to access easy correspondence among various suppliers, for example, radiologists, orthopedics,

architects, and implant organizations. The importance of using 3D printing technology in a medical procedure is centered on these three classes: 3D surgical models, surgical implants and surgical guides. While models and implants can be made utilizing SLA and FDM, guides are printed using SLM, EBM or SLS technology [87].

This contribution reviewed different kinds of facial implants, its designing and manufacturing. Every patient has a different kind of requirement, in every case designer need to design each part for each patient according to their data from CT or MRI scans.

After the medical data is provided by a doctor, designers design the customized implant, such as TMJ implants and mandibles that have been discussed for the facial area. Various 3D designing software such as MIMICS, Solid Works, UG, QT, and others are already used by various researchers. After the successful design of the facial implant, it is further proceeded for simulations to measure its strength. Implants are checked carefully by designers and doctors for the final design approval and then the final design is sent to the implant manufacturer.

Computer-aided design and manufacturing provide an easy and effective way for doctors to design and manufacture an accurate facial implant. Moreover, they diminish operation time and can enable a better way for future specialists to make it simpler to explain the treatment aims to the patient. In this study, manufacturing technologies are also discussed for producing the customized implants in which 3D printing technology is found to be a good manufacturing technology in the sense of time, accuracy and speed.

6.1. Five-year view

Presently, modified facial implants are broadly used in different kinds of medical procedures to improve accuracy and life quality. The benefit of a customized facial implant is to provide an enjoyable life to patients who survived a facial damage.

However, the real process of the design and manufacturing of facial implant is somehow difficult, because various measurements and waiting times are required before the final surgery. The preoperative planning, image processing, and implant design and manufacturing is not only taking time, but also cost-effective and challenging. To handle this process, various possibilities have been established, including image analysis algorithms for preoperative planning, image processing, and implant design. For the design of facial implants, CAD-CAM designers and doctors are involved to make it accurate and useful for the patient. Moreover, a good design software provides a user-friendly interface and can reduce planning and design time.

Funding

This work was supported by grants from National Key R&D Program of China (2017YFB1104100), National Natural Science Foundation of China (81971709; 81828003; M-0019; 8191101624), the Foundation of Ministry of Education of China Science and Technology Development Center (2018C01038), the Foundation of Science and Technology Commission of Shanghai Municipality (19510712200), and Shanghai Jiao Tong University Foundation on Medical and Technological Joint Science Research (ZH20182DA15;YG2019ZDA06;ZH2018QNA23). In addition, it

was supported by the Austrian Science Fund (FWF) KLI 678-B31 and by CAMed (COMET K-Project 871132), which is funded by the Austrian Federal Ministry of Transport, Innovation and Technology (BMVIT), and the Austrian Federal Ministry for Digital and Economic Affairs (BMDW), and the Styrian Business Promotion Agency (SFG). Further, the TU Graz Lead Project 'Mechanics, Modeling and Simulation of Aortic Dissection'. Finally, we want to acknowledge the Overseas Visiting Scholars Program from the Shanghai Jiao Tong University (SJTU) in China.

Declaration of interest

The authors have no relevant affiliations or financial involvement with any organization or entity with a financial interest in or financial conflict with the subject matter or materials discussed in the manuscript. This includes employment, consultancies, honoraria, stock ownership or options, expert testimony, grants or patents received or pending, or royalties.

Reviewer disclosures

Peer reviewers on this manuscript have no relevant financial or other relationships to disclose.

References

Papers of special note have been highlighted as either of interest (*) or of considerable interest (**) to readers.

- Leandro LF, Ono HY, Loureiro CC, et al. A ten-year experience and follow-up of three hundred patients fitted with the Biomet/Lorenz Microfixation TMJ replacement system. *Int J Oral Maxillofac Surg.* **2013**;42:1007–1013.
- Ackland D, Robinson D, Vee P, et al. Design and clinical outcome of a novel 3D-printed prosthetic joint replacement for the human temporomandibular joint. *Clin Biomech.* **2018**;56:52–60.
- Mercuri LG. Temporomandibular joint total joint replacement-TMJ TJR—a comprehensive reference for researchers, material scientists and surgeons. New York: Springer International Publishing; **2016**.
- Kurtoglu C, Kurkcu M, Sertdemir Y, et al. Temporomandibular disorders in patients with rheumatoid arthritis: a clinical study. *Niger J Clin Pract.* **2016**;19(6):715–720.
- Sekou S, Dichen L, Bingheng L, et al. Design and fabrication of custom mandible titanium tray based on rapid prototyping. *Med Eng Phys.* **2004**;26:671–676.
- Sekou S, Yaxiong L, Dichen L, et al. Fabrication of customised maxillo-facial prosthesis using computer-aided design and rapid prototyping techniques. *Rapid Prototyping J.* **2006**;12(4):206–213.
- Chen TM, Wang HJ, Cheng TY, et al. The rationale of mandible reconstruction in advanced oral cancer: alloplastic material versus autogenous vascularized bone graft. *Mater Sci Eng C.* **2000**;13(1/2):49–58.
- Poli T, Ferrari S, Biancha B, et al. Primary oromandibular reconstruction using free flaps and throp plates in cancer patients: a 5-year experience. *Head Neck.* **2003**;25:15–23.
- Pau M, Wallner J, Feichtinger M, et al. Free thoracodorsal, perforator-scapular flap based on the angular artery (TDAP-Scap-aa): clinical experiences and description of a novel technique for single flap reconstruction of extensive oromandibular defects. *J Craniomaxillofac Surg.* **2019**;47:1617–1625.
- Gao J, Dennis J, Solchaga L, et al. Tissue-engineered fabrication of an osteochondral composite graft using rat bone marrow-derived mesenchymal stem cells. *Tissue Eng.* **2001**;7:363–371.
- Singare S, Dichen L, Bingheng L, et al. Customized design and manufacturing of chin implant based on rapid prototyping. *Rapid Prototyping J.* **2005**;11(2):113–118.
- Manmadhachary A, Malyala SK, Kumar R, et al. Design and manufacturing of implant for reconstructive surgery: a case study. *KnE Engineering.* **2017**; 2(1):143–149.
- Park JH, Jo E, Cho H, et al. Temporomandibular joint reconstruction with alloplastic prosthesis: the outcomes of four cases. *J Maxillofacial Plast Reconstructive Surg.* **2017**; 39:6.
- Important outcome from the patients on TMJ reconstruction with alloplastic prosthesis.**
- Naik PK, Kumbi A, Hiregoudar V. Wider necessity of digital image processing in biomedical with its further scope. *Int J Res Trends Innovation.* **2016**;2(1):9–16.
- Suhaimi MA. Image processing in medical applications. *J Inf Technol Impact.* **2003**;3(2):63–68.
- Byrne N, Velasco M, Tandon A, et al. A systematic review of image segmentation methodology, used in the additive manufacture of patient-specific 3D printed models of the cardiovascular system. *J Royal Soc Med Cardiovascular Dis.* **2016**;5:1–9.
- Egger J. Computer design of bio structures. 3D bioprinting for reconstructive surgery techniques and applications. United Kingdom: Elsevier. **2018**. p. 33–73.
- Important review on automatic surgical guides based on computer aided methods**
- Egger J, Wallner J, Gall M, et al. Computer-aided position planning of miniplates to treat facial bone defects. *PLoS ONE.* **2017**;12(8):e0182839.
- Important overview and detailed article on planning of miniplates to treat facial bone defects through computer aided position.**
- Chen X, Li X, Xu L, et al. Development of a computer-aided design software for dental splint in orthognathic surgery. *Sci Rep.* **2016**;6:38867.
- Important overview on the use of 3D softwares in the manufacturing of facial implants and detailed algorithms on development of new software for designing an implant.**
- Kozakiewicz M, Wach T, Szymor P, et al. Two different techniques of manufacturing TMJ replacements - A technical report. *J Craniomaxillofac Surg.* **2017**;45:1432–1437.
- Important techniques provided for the manufacturing of temporomandibular joint replacement.**
- Chepelev L, Wake N, Ryan J, et al. Radiological Society of North America(RSNA) 3D printing Special Interest Group(SIG): guidelines for medical 3D printing and appropriateness for clinical scenarios. *3D Print Med.* **2018**;4:11.
- Vitulano S, Roberto D, Nappi M, et al. Different methods to segment biomedical images. *Pattern Recognit Lett.* **1997**;18(11–13):1125–1131.
- Singare S, Yaxiong L, Dichen L, et al. Fabrication of customized maxilla-facial prosthesis using computer-aided design and rapid prototyping techniques. *Rapid Prototyping J.* **2006**;12(4):206–213.
- Korioth TW, Romilly DP, Hannam AG. Three-dimensional finite element stress analysis of the dentate human mandible. *Am J Phys Anthropol.* **1992**;88:69–96.
- Chen X, Lu X, Xing L, et al. Computer aided implant design for the restoration of cranial defects. *Sci Rep.* **2017**;7:4199.
- Important and detailed overview report on restoration of cranial defects through computer aided design.**
- Egger J, Gall M, Tax A, et al. Interactive reconstructions of cranial 3D implants under MeVisLab as an alternative to commercial planning software. *PLoS ONE.* **2017**;12(3):e0172694.
- Important instructions on cranial 3D implants using commercial planning software.**
- Xu X, Luo D, Guo D, et al. A custom-made temporomandibular joint prosthesis for fabrication by selective laser melting: finite element analysis. *Med Eng Phys.* **2017**;46:1–11.
- Jardini AL, Larosa MA, Filho RM, et al. Cranial reconstruction: 3D biomodel and custom-built implant created using additive manufacturing. *J Craniomaxillofac Surg.* **2014**;4:1877–1884.
- Zheng JS, Chen X, Jiang W, et al. An innovative total temporomandibular joint prosthesis with customized design and 3D printing additive fabrication: a prospective clinical study. *J Transl Med.* **2019**; 17:4.
- Important review study on total temporomandibular joint prosthesis, which help in customized design and 3D printing.**

30. Hsu JT, Huang HL, Tsai MT, et al. Effect of screw fixation on temporomandibular joint condylar prosthesis. *J Oral Maxillofac Surg.* **2011**;69:1320–1328.
31. Chen Q, Bretcanu O, Boccaccini A. Inorganic and composite bioactive scaffolds for bone tissue engineering. *Handbook of Fabrication and Processing of Biomaterials*. Vol. 1. Boca Raton, FL, USA: CRC Press; **2008**. p. 3–43.
32. Zou L, Zhao J, He D. Preliminary clinical study of Chinese standard alloplastic temporomandibular joint prosthesis. *J Craniomaxillofac Surg.* **2019**;47:602–606.
33. Westermarck A. Total reconstruction of the temporomandibular joint. Up to 8 years of follow-up of patients treated with Biomet (®) total joint prosthesis. *Int J Oral Maxillofac Surg.* **2010**;39(10):951–955.
34. Carlos A, Leon L. New perspectives in mercury porosimetry. *Adv Colloid Interface Sci.* **1998**;76(77):341–372.
35. Yanez A, Cuadrado A, Martel O, et al. Gyroid porous titanium structures: a versatile solution to be used as scaffolds in bone defect reconstruction. *Mater Des.* **2018**;140:21–29.
36. Karageorgiou V, Kaplan D. Porosity of 3D biomaterial scaffolds and osteogenesis. *Biomaterials.* **2005**;26:5474–5491.
37. Kaplan F, Hayes W, Keaveny T, et al. Form and function of bone, orthopaedic basic science. *Am Acad Orthop Surgeons*. Vol. 1. **1994**;128–184.
38. Keaveny T, Morgan E, Niebur G, et al. Biomechanics of trabecular bone. *Annu Rev Biomed Eng.* **2001**;3:307–333.
39. Renders G, Mulder L, Ruijven L, et al. Porosity of human mandibular condylar bone. *J Anat.* **2007**;210:239–248.
40. Wieding J, Lindner T, Bergschmidt P, et al. Biomechanical stability of novel mechanically adapted open-porous titanium scaffolds in metatarsal bone defects of sheep. *Biomaterials.* **2015**;46:35–47.
41. Kuboki Y, Takita H, Kobayashi D, et al. BMP-induced osteogenesis on the surface of hydroxyapatite with geometrically feasible and non-feasible structures: topology of osteogenesis. *J Biomed Mater Res.* **1998**;39:190–199.
42. Wieding J, Jonitz A, Bader R. The effect of structural design on mechanical properties and cellular response of additive manufactured titanium scaffolds. *Materials.* **2012**;5:1336–1347.
43. Ponader S, Wilmowsky C, Widenmayer M, et al. In vivo performance of selective electron beam-melted Ti-6Al-4 V structures. *J Biomed Mater Res.* **2010**;92:56–62.
44. Wieding J, Wolf A, Bader R. Numerical optimization of open-porous bone scaffold structures to match the elastic properties of human cortical bone. *J Mech Behav Biomed Mater.* **2014**;37:56–68.
45. Taniguchi N, Fujibayashi S, Takemoto M, et al. Effect of pore size on bone ingrowth into porous titanium implants fabricated by additive manufacturing: an in vivo experiment. *Mat Sci Eng.* **2016**;59:690–701.
46. Moiduddin K, Anwar S, Ahmed N, et al. Computer assisted design and analysis of customized porous plate for mandibular reconstruction. *IRBM.* **2017**;38:78–89.
47. Schek RM, Taboas JM, Hollister SJ, et al. Tissue engineering osteochondral implants for temporomandibular joint repair. *Orthodontics Craniofacial Res.* **2005**;8:313–319.
48. Chen J, Luo C, Zhang C, et al. Design and fabrication of the custom-made titanium condyle by selective laser melting technology. *Chin J Stomatol.* **2014**;49:625–630.
49. Chelule CL. Fabrication of medical models from scan data via rapid prototyping techniques. [Cited 2007 Mar 10].
50. Ataee A, Li Y, Fraser D, et al. Anisotropic Ti-6Al-4V gyroid scaffolds manufactured by electron beam melting (EBM) for bone implant applications. *Mater Des.* **2018**;137:345–354.
51. Yáñez A, Cuadrado A, Martel O, et al. Gyroid porous titanium structures: a versatile solution to be used as scaffolds in bone defect reconstruction. *Mater Des.* **2018**;140:21–29.
52. Ataee A, Li Y, Brandt M, et al. Ultrahigh-strength titanium gyroid scaffolds manufactured by selective laser melting (SLM) for bone implant applications. *Acta Materialia.* **2018**;158:354–368.
53. Yan C, Hao L, Hussein A, et al. Ti-6Al-4V triply periodic minimal surface structures for bone implants fabricated via selective laser melting. *J Mech Behav Biomed Mater.* **2015**;51:61–73.
54. Al-Ketan O, Al-Rub RK, Rowshan R. Mechanical properties of a new type of architected interpenetrating phase composite materials. *Adv Mater Technol.* **2017**;176:9–19.
55. Fink S, Atkinson A. Personalized implants restore smiles. **2018**. Available from: [ansys.com](https://www.ansys.com).
56. Sinno H, Tahiri Y, Gilardino M, et al. Engineering alloplastic temporomandibular joint replacements. *Mcgill J Med.* **2011**;13:63–70.
57. Bai G, He D, Yang C, et al. Application of digital templates to guide total alloplastic joint replacement surgery with biomet standard replacement system. *J Craniomaxillofac Surg.* **2014**;72(12):2440–2452.
58. Akmal J, Salmi M, Mäkitie A, et al. Implementation of industrial additive manufacturing: intelligent implants and drug delivery systems. *J Funct Biomater.* **2018**;9(3):1–14.
59. Hoffmann B, Sepehrnia A. Tailored implants for alloplastic cranioplasty - clinical and surgical considerations. *Acta Neurochirurgica Suppl.* **2005**;93(93):127–129.
60. Wicher J, Ruud R, Arjan V, et al. Digital planning of cranial implants. *Br J Oral Maxillofac Surg.* **2013**;51(5):450–452.
61. Zhou XY, Yang C, Chen MJ, et al. Digital resection and reconstruction of TMJ synovial chondrosarcoma involving the skull base: report of a case. *Int J Clin Exp Med.* **2015**;8:11589–11593.
62. Acklanda C, Robinson D, Redhead M, et al. A personalized 3D-printed prosthetic joint replacement for the human temporomandibular joint: from implant design to implantation. *J Mech Behav Biomed Mater.* **2017**;69:404–411.
63. Zheng JS, Liu XH, Chen XZ, et al. Customized skull base-temporomandibular joint combined prosthesis with 3Dprinting fabrication for craniomaxillofacial reconstruction: a preliminary study. *Int J Oral Maxillofac Surg.* **2019**;48(11):1440–1447.
64. Bhargava D, Neelakandan RS, Singh VD, et al. Total alloplastic temporomandibular joint: proposal for a total Titanium Condylar Prosthesis with UHMWPE Joint Fossa Design (DARSN TM joint prosthesis). *Acta Sci Orthop.* **2018**;1(1):22–27.
65. Larry M, Mercuri LG, Schneiderman ED, et al. Twenty year follow-up study on a patient-fitted temporomandibular joint prosthesis: the Techmedica/TMJ concepts device. *J Oral Maxillofacial Surg.* **2015**;73:952–960.
66. Chen X, Wang Y, Mao Y, et al. Biomechanical evaluation of Chinese customized three dimensionally printed total temporomandibular joint prostheses: a finite element analysis. *J Craniomaxillofacial Surg.* **2018**;46(9):1561–1568.
67. Zhang SY, Liu H, Yang C, et al. Modified surgical techniques for total alloplastic temporomandibular joint replacement: one institution's experience. *J Craniomaxillofac Surg.* **2015**;43(6):934–939.
68. Wolford LM, Karras SC. Autologous fat transplantation around temporomandibular joint: total joint prostheses: preliminary treatment outcomes. *J Oral Maxillofacial Surg.* **1997**;55:3:245–251.
69. Mercuri LG, Alcheikh F, Woolson R. Outcomes of total alloplastic replacement with peri-articular autogenous fat grafting for management of reankylosis of the TMJ. *J Oral Maxillofac Surg.* **2008**;66(9):1794–1803.
70. Siegmund BJ, Winter K, Meyer-Marcotty P, et al. Reconstruction of the temporomandibular joint: a comparison between prefabricated and customized alloplastic prosthetic total joint systems. *Int J Oral Maxillofac Surg.* **2019**;48(8):1066–1071.
71. Zheng JS, Chen XZ, Jiang WB, et al. An innovative total temporomandibular joint prosthesis with customized design and 3D printing additive fabrication: a prospective clinical study. *J Transl Med.* **2019**;17:4.
72. Elledge R, Mercuri LG, Speculand B. Extended total temporomandibular joint replacements: a classification system. *Br J Oral Maxillofac Surg.* **2018**;56(7):578–581.
73. Kirchheimer S, Sainuddin S, Bojanic S, et al. Simultaneous custom-made replacement of the temporomandibular joint and cranioplasty. *Br J Oral Maxillofacial Surg.* **2013**;51(5):e70–e71.

•• **Important article to help us find effect of pore size on bone ingrowth into porous titanium implants using additive manufacturing techniques.**

74. Chen MJ, Yang C, Zheng JS, et al. Skull base erosion resulting from primary tumor of the temporomandibular joint and skull base region: our classification and reconstruction experience. *J Oral Maxillofac Surg.* **2018**;76(6):1345–1354.
75. Zhou XY, Yang C, Chen MJ, et al. Digital resection and reconstruction of TMJ synovial chondrosarcoma involving the skull base: report of a case. *Int J Clin Exp Med.* **2015**;8(7):11589–11593.
76. Rengier F, Mehndiratta A, Teng-Kobligk H. 3D printing based on imaging data: review of medical applications. *Int J Comput Assist Radiol Surg.* **2010**;5:335–341.
77. Fletcher J, Windolf M, Richards G, et al. Importance of locking plate positioning in proximal humeral fractures as predicted by computer simulations. *J Orthop Res.* **2019**;37:957–964.
78. Fang C, Wong TM, Lau TW, et al. Infection after fracture osteosynthesis – part I: pathogenesis, diagnosis and classification. *J Orthop Surg.* **2017**;25(1):1–13.
79. Morais A, Egger J, Alves V Automated computer-aided design of cranial implants using a deep volumetric convolutional denoising autoencoder. *WorldCist'19*; **2019**. p. 151–160.
80. Gsaxner C, Pepe A, Wallner J, et al. Markerless Image-to-face registration for untethered augmented reality in head and neck surgery. *MICCAI*; **2019**. p. 236–244.
81. Egger J, Gall M, Wallner J, et al. HTC Vive MeVisLab integration via OpenVR for medical applications. *PLoS ONE.* **2017** Mar;12(3):e0173972.
 - **Important because it shows the trend for future automatic implant manufacturing with Artificial Intelligence.**
82. Kim GB, Lee S, Kim H, et al. Three-dimensional printing: basic principles and applications in medicine and radiology. *Korean J Radiol.* **2016**;17(2):182–197.
83. Unwin PS, Eshraghi A. Custom implants. In: Ritacco LE, Milano FE, Chao E, editors. *Computer-assisted musculoskeletal surgery: thinking and executing in 3D*. Switzerland: Springer; **2016**. p. 181–198.
84. Fan H, Fu J, Li X, et al. Implantation of customized 3-D printed titanium prosthesis in limb salvage surgery: a case series and review of the literature. *World J Surg Oncol.* **2015**;13:308.
85. Wong KC, Kumta SM, Geel NV, et al. One-step reconstruction with a 3D-printed, biomechanically evaluated custom implant after complex pelvic tumor resection. *Comput Aided Surg.* **2015**;20(1):14–23.
86. Wong KC, Kumta SM, Chiu KH, et al. Computer assisted pelvic tumor resection and reconstruction with a custom-made prosthesis using an innovative adaptation and its validation. *Comput Aided Surg.* **2007**;12(4):225–232.
87. Shilo D, Emodi O, Blanc O, et al. Printing the future—updates in 3D printing for surgical applications. *Rambam Maimonides Med J.* **2018**;9(3):e0020.