American Journal of Health Research
2026, Vol. 14, No. 1, pp. 33–39
https://doi.org/10.11648/j.ajhr.20261401.15

SciencePG
Science Publishing Group

Review Article

Computer-Aided Design and Manufacturing in Facial Prosthetics: A Review of the Literature

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Abstract

Introduction: Nowadays, CAD/CAM is used to treat facial substance loss as part of surgical treatment or prosthetic rehabilitation. The aim of our work is to review the literature in order to compare digital manufacturing technology with other conventional methods. *Materials and methods:* This is a literature review based on a search carried out at the beginning of 2022 on publications from the last ten years. A keyword-based search algorithm was used to highlight the most relevant articles on the topic in question. *Results and discussion:* After reading the 29 articles selected in their entirety, we make a critical comparison between the manufacture of facial prostheses by the digital method and the conventional method in all its aspects, to determine the contribution of CAD/CAM to the rehabilitation of facial substance loss both surgically and prosthetically. *Conclusion:* Our review concluded that digital technology and 3D printing have facilitated the fabrication of facial prostheses with maximum comfort for both patient and practitioner. The combination of these techniques with conventional techniques is sometimes essential for better results.

Keywords

Facial Sustance Loss, Facial Prostheses, 3D Printing

1. Introduction

Trauma, cancer treatment and congenital diseases can result in facial defects requiring complex management. These defects can be restored by surgical reconstruction or with prostheses. The results achieved in a large number of patients are often unsatisfactory for surgical solutions. Thus, prosthetic rehabilitation with facial prostheses is indispensable, and patient satisfaction with this treatment is significantly higher [1]. The traditional manufacture of epitheses is labour-intensive and effort-consuming [1]. For a long time, there was no alternative to this approach, but since the advent of three-dimensional (3D) scanners, 3D software and rapid prototyping technology, traditional techniques have been replaced by digital equivalents. Consequently, the aim of this work is to review the literature to determine the current status of 3D technology used in the prosthetic rehabilitation of facial defects (ear, nose and orbit), define its advantages and disadvantages, and compare this technology with conventional methods [1].

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Received: 9 December 2024; **Accepted:** 25 December 2024; **Published:** 30 January 2026

Technological evolution never stops, and the future of facial prostheses is under construction. These prostheses, which are currently substance substitutes without any life, will probably be able to express themselves in the future under brain control.

2. Materials and Methods

1) Sources and search strategies:

A bibliographic literature search was carried out at the beginning of 2022, on publications from the last ten years (2012 to 2022), using the electronic databases Pub Med, Google Scholar, Scopus and Science Direct. A search algorithm "facial prosthesis, computer, 3D, extra-oral prosthesis, rapid prototyping, facial prosthesis, silicone prosthesis, facial defect..." was used to highlight the most relevant articles concerning the topic.

2) Selection and evaluation of articles:

Search results were imported into Zotero and duplicates were removed. Articles included were those no older than 10 years, studies, literature reviews and clinical cases.

3) Selected publications:

The article selection procedure is summarized in the flow chart (Figure 1). The search algorithm in the various databases identified 79 articles. After removing duplicates, 68 articles were retained for reading titles and abstracts, 43 articles were retained for full reading and only 29 articles were finally selected.

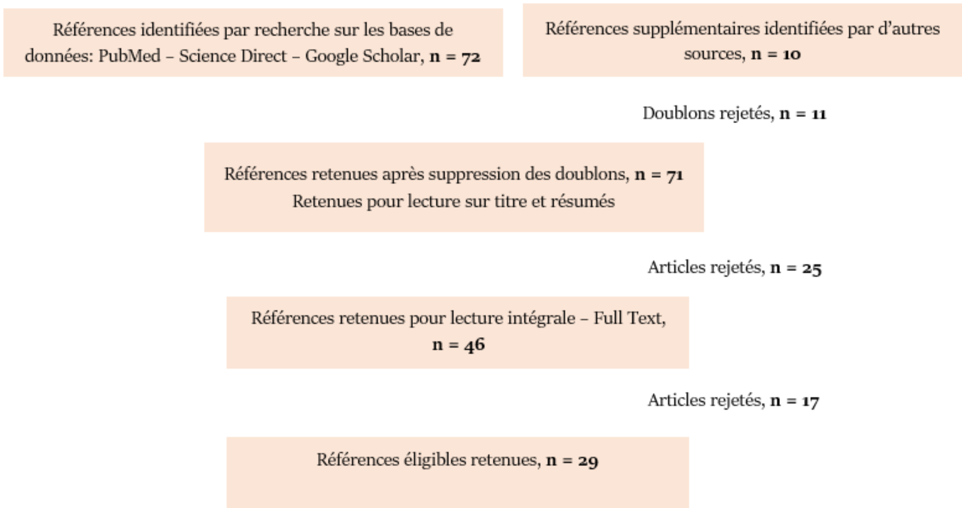

Figure 1. *Flow diagram.*

3. Results and Discussion

In 1973, with François Duret's "Empreinte Optique" thesis, the foundation stone for dental CAD/CAM was laid. The idea was to reduce the repetitive gestures involved in the manufacture of dental prostheses to their simplest form. His work is a real starting point, since he has proposed the entire system: impression + top surface machining + bottom surface machining. We'll have to wait a little longer to see a complete CAD/CAM procedure in maxillofacial and body prosthetics, but the use of optical impressions and digital data processing has been spreading in medicine since the late 80s [2].

A number of methods are currently available:

- optical cameras can be used to capture details of intra-oral structures in film or photo sequences. The cameras currently available feature high-performance optical systems in terms of resolution, with open or non-open systems that allow files to be exported in a standard format familiar to most laboratory machinists. They also boast a high quality graphic interface, enabling fine reproduction of fabric colors.

- design software (CAD) processes data and enables product design by computer.

- the machine tool (FAD) machines the product from the data transmitted to the machine tool.

Reading the articles enabled us to:

1- Compare the manufacture of facial prostheses using new digital technologies and conventional methods in different respects.

For data storage, I. Van Heerden and A. Fossey [3], point out that CAD/CAM enables digital data to be collected and stored for repeated use. For them, CAD/CAM is equipped with a number of effective tools for the digital manufacture of facial prostheses, such as the mirroring technique, which makes it possible to manufacture a prosthesis similar to contralateral anatomical structures such as the ear and eyes. Other tools, such as the addition of small facial details, are also capable of enhancing the aesthetic result. Thus, CAD/CAM makes it possible to preFigure the final aesthetic result by involving the patient, then digitally store the information. This enables the facial prosthesis to be produced at a later date, without the patient being present.

With regard to working time, Nafij B Jamayet et al [4] found that the CAD/CAM facial prosthesis production line required fewer sessions, and was therefore less tiring for both patient and practitioner. As a result, the protocol is faster and the clinical results satisfactory. I.van Heerden and A. Fossey [3], agree that the 3D printer speeds up the manufacturing process and reduces costs and stress for the patient. Ernesto H. et al, in their study carried out in 2020 [5], also agree that CAD/CAM makes it possible to reduce the time dedicated to prosthetic fabrication, and to overcome the technical obstacles that limit certain patients accès to facial prostheses, especially since product delivery is no longer a restriction as 'remote printing' by local distributors and service providers has become accessible. The fabrication of a conventional facial prosthesis by an experienced and gifted maxillofacial prosthetist requires 1 to 2 weeks, in contrast digital fabrication can be done within 46 hours (Table 1) [7].

Hugo I. and al [6] compared the working time of the two techniques, and concluded that the digital method reduced the prosthetist's working time. Similarly, Waqas Tanveer et al [7] made another comparison between the time needed to manufacture a nasal prosthesis using the digital method and the conventional method, and concluded that the former is 3 hours faster than the latter (table 2). Leanne Sykes et al [8] spent 6 hours sculpting a wax model of an ear prosthesis, whereas CAD/CAM was used to design the same prosthesis in just 3 hours.

Table 1. *Estimated time required to manufacture of a facial prosthesis using the digital method [5].*

Step	Time
1 Facial topographic mapping	1 hour
2 Digital sculpting and adaptation of facial data	4 hours
3 Digital design of 3D	2 hours
4 Mixing pigments and silicone	1 hour
5 3D printing the digitally designed mold	20 hours
6 Casting the silicone prosthesis	16 hours
7 Detailing	2 hours
Total time	46 hours

Table 2. *Comparison between digital and conventional and conventional production of a nasal prosthesis [7].*

Procedures	Production time	
	Digital	**Conventionnelle**
Recording facial defects	3D Scan 10 min	Conventional impress 20 min
Sculpture	Digital 60 min	Manual wax-up (laboratory) + Fitting (clinic) 120 – 30 min
Coloring	Digital coloring 30 min	Silicone mixing and skin-tone adaptation 60 min
Nose reproduction	3D digital printing 180 min	Flasking – Production du moufle – Curing – Finition 60 – 30 – 120 – 30 min
External coloring	30 min	30 min
Overall time	310 min	500 min

The aesthetic result is a very important parameter in this comparison, and our review shows that the manufacture of a CAD/CAM facial prosthesis provides maximum symmetry and a more natural appearance. Our authors propose the colorimeter-based digital impression technique (E-Skin by Spectro Match), which enables skin tone to be measured and matched to a palette in the Spectro Match database. Nina Ariani et al. in their article [9] confirm that digital systems such as 'Spectrophotometers', 'Fiber-optic devices' and 'Imaging color analyzer modules' enable good Color-Matching and, consequently, good aesthetic results.

Raghavendra Adaki [10], present a clinical case of a facial defect which shows that creating the surface texture of the prosthetic cheek to mimic the elevations, depressions and skin tone of the normal side is very difficult using conventional methods, and that using CAD/CAM has made the task completely easier. Van der Meer et al. point out in their article [1] that 3D printers have the disadvantage of limited resolution due to the size of the powder particles, which influences the color of the materials used, making it more difficult to match this color to the patient's skin color. Another study [11] shows that the same facial prostheses fabricated by conventional techniques do not have the same color as those fabricated by CAD/CAM. Thus, the combination of the two techniques delivers better aesthetic results. All facial epithesis materials are subject to wear over time, and will need to be replaced or made up after several months or years (12 months to 3 years), as a result of discoloration, degradation, wear, or damage due to mishandling [12].

In terms of mechanical and physical properties, Rena L. J. Cruz et al [13] made a mechanical comparison between the direct silicone-printed prosthesis and the conventional prosthesis, and reported that the former was better in terms of hardness. On the other hand, the latter is better in terms of compressive strength, ductility, yield strength, resistance to cracking and elasticity. They also report that scanners expose too much radiation, and create a dangerous interaction with the magnetic field in patients with metal implants, but prefer the use of laser scanners, advising that the patient should not move during scanning to avoid tissue deformation. Intra-oral scanners, on the other hand, have good resolution but a reduced field of view.

As far as precision is concerned [1], conventional impression materials (alginate, silicones, plaster) can reproduce details of 20 µm, but unfortunately this precision is not yet achieved with these 3D scanners (laser, CT, MRI, photo, structured light).

On the other hand, the conventional impression procedure is more complicated [15], as the practitioner must take into account the diversity of soft and hard tissues, their mobility, the presence of undercuts and the distortion of the impression material due to its weight and consistency. Certain clinical situations, such as trismus, can complicate conventional impression procedures and interfere with the precision of the materials used. In such cases, the digital impression will have its place and simplify the work. A clinical study by Unkovskiy et al. in 2018 shows that the direct-printed facial prosthesis is poorly adapted at the marginal level compared with the conventional prosthesis. This is due to the thickness of the layer of printed material, which is relatively greater (0.4 mm) than the thickness used in the conventional technique (0.2 mm).

The study by Nafij B. Jamayet [4] shows that the major disadvantage of direct digital printing of a facial prosthesis is that it does not produce prosthetic margins adapted to the structures associated with the loss of substance. To overcome this problem, these authors propose a combination of CAD/CAM and the conventional method, i.e. they take a conventional impression of the facial defect to obtain a working model, then a wax component which will be tried in and then adapted directly to the edges of the loss of substance, then scanned and fabricated by CAD/CAM. Rena L. J. Cruz et al. made a comparison in their article [13] between the digital and conventional production of facial prostheses, and found that the final result was considered satisfactory by the patient for both techniques, but as experts themselves, they preferred the aesthetics obtained by CAD/CAM but the marginal adaptation obtained by the conventional technique (Figure 2).

The conventional technique requires a primary impression to produce a custom tray, followed by an anatomofunctional impression of the defect using a light consistency material. Added to this celà is the weight of the material and the posture required of the patient during setting. This time-consuming and uncomfortable process for both patient and practitioner can limit the latter's motivation for prosthetic treatment [10]. However, digital scanning or optical impressions are more comfortable. It avoids deformation of facial tissues during facial molding [14].

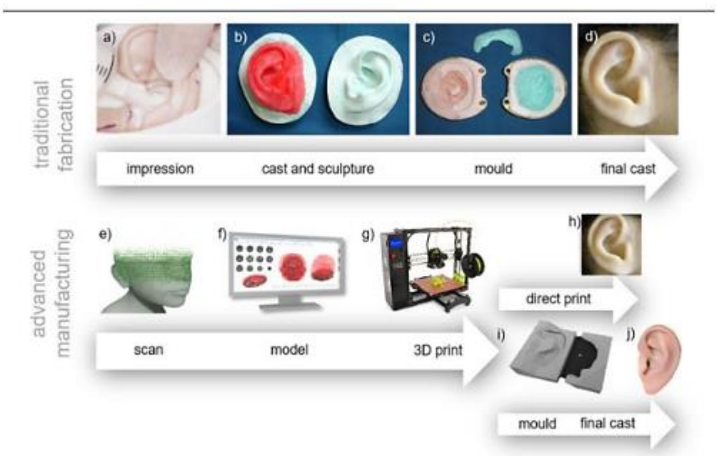

Figure 2. *Comparison between traditional and digital technology.*

Concerning retention systems for facial prostheses, authors Nina Ariani et al [11], say that the better the retention of the facial prosthesis, the more satisfied the patient. Adhesive retention systems are unsatisfactory for patients because of prosthetic mobility, dislodgement during function and skin irritation due to the adhesive. Implant-based retention systems, on the other hand, are much more preferred due to their ease of insertion and removal. The combination of implants as retention devices with CAD/CAM technology is called for to improve patient acceptance of the prosthesis [16, 11].

According to Trevor D. Crafts et al [17], the increase in the price of 3D printers and software can be explained by the fact that the use of CAD/CAM in the medical field is subject to a limited list of authorized materials, and that 3D printers for facial prostheses that enable direct printing are not widely available. These authors add that software for CAD facial prosthesis design is very limited and expensive. The market for this digital technology is less active, which limits the attractiveness of IT companies to develop such software. According to I. van Heerden and A. Fossey [3], some devices are still expensive, which limits their use, and several countries classify the prosthetic rehabilitation of facial defects in the cosmetic field, which does not justify their reimbursement. All these authors share the same opinion, and propose the collaboration and sharing of 3D printers and software (CAD) between certain specialized medical departments and units.

Comparing the cost of manufacturing an ear prosthesis using the conventional and digital methods, based on purchase payments and laboratory costs in Mexico (Table 3), Hugo I. et al [6] and Leonardo Ciocca [18] show that the prosthesis manufactured using the digital method is 23% less expensive than that manufactured using the conventional method, and that savings of up to 50% can be achieved using the digital method.

Table 3. *Comparison of dental laboratory fees for the manufacture of an ear prosthesis using both digital and conventional techniques [14].*

Description	**Conventional technique**	**Digital technology**
Prosthetic work rates in USD	350	135
Engineering specialist rates in USD	-	270
RP (Rapid Prototyping) machine labor cost in USD	-	65
Material prices in USD	100	110
Total in USD	750	580

2- Determine the contribution of CAD/CAM to the rehabilitation of facial substance loss:

3.1. In Surgical Treatment

It enables pre-therapeutic planning using a three-dimensional radiological examination. Imaging is then studied using 3D modeling software capable of simulating bone sections, bone movements and the results obtained, and a reconstruction model is then proposed. This model is then printed, enabling exact copies of the patient's facial structures to be obtained, as well as the creation of custom-made parts to help fill any loss of substance.

Some of these models can be used as synthetic training models for surgeons. Others are used as cutting guides and osteosynthesis plates.

Dental implant planning has also benefited from CAD developments. For example, virtual dental implants are positioned according to antagonistic occlusal landmarks, before the trajectory of the bone reconstruction is mapped out. Once the implants have been positioned, the trajectory of the graft conformation is traced so as to join the ends of the bone resection, while passing through the implants (Figure 3). Once the conformation is displayed, segment adjustments are made to ensure proper distribution of bone volume around the implants [2, 19].

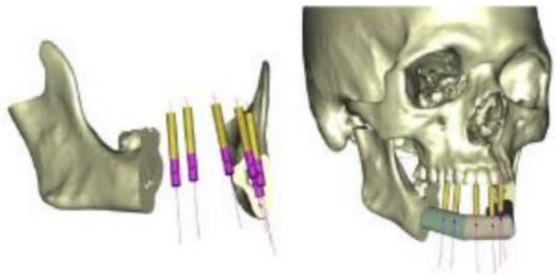

Figure 3. *Reconstruction planning based on implant positioning the antagonist dental arch [19].*

3.2. In Prosthetic Treatment

Typical sites for craniofacial prosthetic rehabilitation include the orbital, nasal and auricular regions. Prostheses are considered medically necessary because of the functional benefits they offer in warming the air, maintaining cavity moisture, protecting fragile tissues, modulating speech and providing support. The treatment of craniofacial defects with prostheses traditionally involves the creation of a bespoke device usually made of polydimethylsiloxane (PDMS) to replace missing tissue and cover underlying tissue. The workflow for creating these devices has remained relatively unchanged for many years. However, the use of advanced 3D imaging techniques (including surface laser scanning and stereo photogrammetry) combined with 3D printing has evolved and allows us by several methods to directly print fully colorized facial prostheses which could considerably reduce the time and cost of manufacturing such prostheses [19].

Other applications of CAD/CAM in reconstructive surgery for facial substance loss have been raised by Rena L. J. Cruz et al [13], such as the manufacture of medical devices, including 'scaffolds' that allow cartilage tissue to grow and maintain itself 8 weeks after surgery [20]. Trevor D. Crafts et al [17] have also reported on tissue regeneration scaffolds and implants in titanium and alphatricalcium phosphate bone, which are implanted in patients for surgical-prosthetic maxillofacial reconstruction.

3- Update on the latest technologies applied in facial prosthetics:

Authors Rui Li et al. show in their articles [21, 22] published in 2018 and 2022 that several types of brain control systems have been applied in the rehabilitation field. As an alternative scheme for balancing user fatigue and the accuracy of brain-computer interface (BCI) systems, facial expression-based brain control technologies have been proposed in the form of new Brain Computer Interface (BCI) systems. The latter, also known as a direct neural interface (DNI), is a communication channel between the brain and an external device, such as a computer or electronic device. The purpose of these devices is to study the brain and assist and repair human cognitive functions [23]. Unfortunately, existing algorithms fail to identify the most relevant features of electroencephalogram (EEG) signals, further limiting performance. To address this problem, an algorithm is proposed for facial expression Systems BCI (FE-BCI), using a convolutional neural network (CNN) combined with a genetic algorithm (GA). The CNN was applied to extract features and classify them. The GA was used for hyper-parameter selection to extract the most relevant parameters.

Research in this field is becoming more and more a part of everyday life, and results in facial prosthetics are not yet significant [24].

4. Conclusion

The three main operational stages of the conventional process chain for the manufacture of facial prostheses can be largely assisted or replaced by the introduction of various technological advances. The use of these technological interventions can have a low, medium or high impact on the conventional process chain, depending on the technologies used:

At a low level of impact, footprint data is collected digitally and a reference model is built from the collected data, while the rest of the conventional operational steps remain the same.

At the medium level, digital data are used to design the reference model and the prosthesis model (mold/flask), which are 3D printed to test accuracy and the final aesthetic result.

Finally, and at a high level of impact, all technological interventions are used in a holistic manner, enabling a prosthesis to be printed directly in the desired material [25].

In summary, our study demonstrates the ease of use and integration of advanced digital technologies for the efficient production of a complex facial prosthesis that traditionally requires an anaplastologist/prosthetist trained in the art and knowledge of fabrication to sculpt the unit by hand. The results show that the digital workflow can produce a facial prosthesis with good facial symmetry, skin tone matching, prosthesis fit and wearing comfort. Archived data sets enable fast, precise digital manipulation to refine the prosthesis' edge-skin interface or touch up any defects in the unit manufactured without the patient's presence. This new method of facial topography, 3D printing and molding has the potential to improve global access to facial prostheses for an underserved population [26]. As for prostheses controlled by the brain through the FE-BCI system, experimental results demonstrate high efficacy for amputee patients [27].

If facial prostheses manage to use the FE-BCI system to be controlled by the brain, a more realistic appearance will be given to these prostheses during facial expression, enabling the patient to relive life more naturally [28]. This is the notion of facial neuro-epithesis.

Abbreviations

3D	Three-dimensional
CAD/CAM	Computer-aided Design and Manufacturing
CT	Transit Center
MRI	Magnetic Resonance Imaging
IT	Information Technologies
PDMS	Polydimethylsiloxane
BCI	Brain-computer Interface
DNI	Direct Neural Interface
EEG	Electroencephalogram
FE	Facial Expression
CNN	Convolutional Neural network
GA	Genetic Algorithm

Conflicts of Interest

The authors declare no conflicts of interest.

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