

Surgical Engineering in Cranio-Maxillofacial Surgery: A Literature Review

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Submitted March 2011. Accepted for publication August 2011

ABSTRACT

A systematic review of the literature concerning surgical engineering in cranio-maxillofacial surgery was performed. A PubMed search yielded 1721 papers published between 1999 and 2011. Based on the inclusion/exclusion criteria, 1428 articles were excluded after review of titles and abstracts. A total of 292 articles were finally selected covering the following topics: finite element analysis (n = 18), computer-assisted surgery (n = 111), rapid prototyping models (n = 41), preoperative training simulators (n = 4), surgical guides (n = 23), image-guided navigation (n = 58), augmented reality (n = 2), video tracking (n = 1), distraction osteogenesis (n = 19), robotics (n = 8), and minimal invasive surgery (n = 7). The results show that surgical engineering plays a pivotal role in the development and improvement of cranio-maxillofacial surgery. Some technologies, such as computer-assisted surgery, image-guided navigation, and three-dimensional rapid prototyping models, have reached maturity and allow for multiple clinical applications, while augmented reality, robotics, and endoscopy still need to be improved.

Keywords: engineering, maxillofacial, craniofacial, review, surgery

1. INTRODUCTION

Cranio-maxillofacial surgery (CMF) represents a broad range of sub-specialties, such as maxillofacial oncological surgery (resection of tumors and reconstruction of the site with different types of grafts), craniofacial corrective surgery of malformative syndromes (i.e., craniostenoses, or cleft lip palate), orthognathic surgery and distraction osteogenesis (to correct maxillomandibular dysmorphoses), maxillofacial trauma surgery and associated reconstructive maxillofacial surgery, and implantology. Surgical engineering in CMF surgery is present at all levels of the CMF clinical workflow, from diagnostic tools to preoperative planning, intra-operative guidance and transfer of preoperative planning to the operative theater. This literature review presents a broad overview of the implications of surgical engineering in CMF surgery.

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2. METHODS

The literature search was performed on Medline PubMed by one researcher. The inclusion criteria were as follows: maxillofacial surgery, craniofacial surgery, implantology, distraction osteogenesis, orthognathic surgery, cleft lip palate surgery, traumatology, finite elements analysis, technology, robotics, virtual reality, augmented reality, haptic, computer-assisted surgery, computer-assisted surgical planning, computer-assisted guides, rapid prototyping, three-dimensional (3D) facial morphology, maxillofacial simulators, maxillofacial endoscopy, maxillofacial surgical hardware, cranioplasty, craniotomy, image-guided surgery, CMF navigation, endoscopy, temporomandibular joint, facial nerve, virtual occlusion, holography, CT scanner, and MRI. The exclusion criteria consisted of animal studies, in vitro studies, tissue engineering, prosthetics, orthodontics, dentistry, laser surgery, laser scanner, piezosurgery, plates, facial protection, jaw tracking, and telemedicine. Articles without an abstract were also excluded.

We used two main search formulas. The first formula was constructed for a broad research of articles dealing with surgical engineering and craniofacial surgery. This formula was formed by association between MeSH Terms (surgical procedures, operative, engineering, and skull) and the following free text words: surgical engineering AND cranial (((“surgical procedures, operative”[MeSH Terms] OR (“surgical”[All Fields] AND “procedures”[All Fields] AND “operative”[All Fields]) OR “operative surgical procedures”[All Fields] OR “surgical”[All Fields]) AND (“engineering”[MeSH Terms] OR “engineering”[All Fields])) AND (“skull”[MeSH Terms] OR “skull”[All Fields] OR “cranial”[All Fields]) AND “humans”[MeSH Terms])). The only limit was human studies. No limits were set on the language or date. We obtained a total of 334 articles, of which 314 were excluded based on the title and the abstract. Twenty articles were selected for review.

The second main formula was constructed to find articles about surgical engineering and maxillofacial surgery. We preferred to use the word “technology” in the second formula to search specifically for articles aimed at surgical engineering instead of tissue engineering. We used an association between MeSH Terms (surgery, oral; and technology) and the following free words: maxillofacial surgery technology ((“surgery, oral”[MeSH Terms] OR (“surgery”[All Fields] AND “oral”[All Fields]) OR “oral surgery”[All Fields] OR (“maxillofacial”[All Fields] AND “surgery”[All Fields]) OR “maxillofacial surgery”[All Fields]) AND (“technology”[MeSH Terms] OR “technology”[All Fields])) AND (“humans”[MeSH Terms] AND “2001/02/22”[PDat] : “2011/02/19”[PDat])). The first limit was human studies, and the second limit was to search over the last ten years. No limits were set on the language. We found a total of 967 articles, and 835 of them were excluded based on title-abstract sifting. The remaining 131 were selected for review. To complete the general broad search, we added seven specific formulas based on MeSH terms and free terms:

1. finite element analysis AND maxillofacial surgery ((“finite element analysis”[MeSH Terms] OR (“finite”[All Fields] AND “element”[All Fields] AND “analysis”[All Fields]) OR “finite element analysis”[All Fields]) AND (“surgery, oral”[MeSH Terms] OR (“surgery”[All Fields] AND “oral”[All Fields]) OR “oral surgery”[All Fields] OR (“maxillofacial”[All Fields] AND

- “surgery”[All Fields]) OR “maxillofacial surgery”[All Fields])) NOT plates[All Fields] AND (“humans”[MeSH Terms] AND English[lang] AND “2008/06/26”[PDat] : “2011/06/25”[PDat]) with 40 articles found, 36 articles excluded, and 4 articles selected;
- 2.- haptic AND maxillofacial surgery (haptic[All Fields] AND (“surgery, oral”[MeSH Terms] OR (“surgery”[All Fields] AND “oral”[All Fields]) OR “oral surgery”[All Fields] OR (“maxillofacial”[All Fields] AND “surgery”[All Fields]) OR “maxillofacial surgery”[All Fields])) AND (“humans”[MeSH Terms] AND English[lang] AND “2008/06/26”[PDat] : “2011/06/25”[PDat]) with 4 articles found, 3 articles excluded, and 1 article selected;
 3. computer-assisted surgery AND maxillofacial surgery (computer-assisted[All Fields] AND “planning”[All Fields] AND (“surgery, oral”[MeSH Terms] OR (“surgery”[All Fields] AND “oral”[All Fields]) OR “oral surgery”[All Fields] OR (“maxillofacial”[All Fields] AND “surgery”[All Fields]) OR “maxillofacial surgery”[All Fields])) AND (“humans”[MeSH Terms] AND English[lang] AND “2008/06/26”[PDat] : “2011/06/25”[PDat]) with 120 articles found, 111 articles excluded or duplicated, and 9 articles selected;
 4. computer-assisted navigation AND maxillofacial surgery computer-assisted[All Fields] AND navigation[All Fields] AND (“surgery, oral”[MeSH Terms] OR (“surgery”[All Fields] AND “oral”[All Fields]) OR “oral surgery”[All Fields] OR (“maxillofacial”[All Fields] AND “surgery”[All Fields]) OR “maxillofacial surgery”[All Fields])) AND (“humans”[MeSH Terms] AND English[lang] AND “2008/06/26”[PDat] : “2011/06/25”[PDat]) with 42 articles found, 26 excluded or duplicated, and 16 articles selected;
 5. distraction osteogenesis AND maxillofacial surgery ((“osteogenesis, distraction”[MeSH Terms] OR (“osteogenesis”[All Fields] AND “distraction”[All Fields]) OR “distraction osteogenesis”[All Fields] OR (“distraction”[All Fields] AND “osteogenesis”[All Fields])) AND (“technology”[MeSH Terms] OR “technology”[All Fields]) AND (“surgery, oral”[MeSH Terms] OR (“surgery”[All Fields] AND “oral”[All Fields]) OR “oral surgery”[All Fields] OR (“maxillofacial”[All Fields] AND “surgery”[All Fields]) OR “maxillofacial surgery”[All Fields])) AND (“humans”[MeSH Terms] AND English[lang])), with 40 articles found, 31 excluded or duplicated, and 9 articles selected;
 6. maxillofacial surgery AND robot ((“surgery, oral”[MeSH Terms] OR (“surgery”[All Fields] AND “oral”[All Fields]) OR “oral surgery”[All Fields] OR (“maxillofacial”[All Fields] AND “surgery”[All Fields]) OR “maxillofacial surgery”[All Fields]) AND robot[All Fields]) AND (English[lang] AND “2001/07/15”[PDat] : “2011/07/12”[PDat]) 41 articles found, 41 excluded or duplicated;
 7. minimal invasive surgery AND maxillofacial surgery minimal[All Fields] AND invasive[All Fields] AND (“surgery, oral”[MeSH Terms] OR (“surgery”[All Fields] AND “oral”[All Fields]) OR “oral surgery”[All Fields] OR (“maxillofacial”[All Fields] AND “surgery”[All Fields]) OR “maxillofacial surgery”[All Fields])) AND (“humans”[MeSH Terms] AND

English[lang] AND “2008/06/27”[PDat] : “2011/06/26”[PDat]) with 37 articles found, 34 articles excluded, and 3 articles selected.

Five of the seven specific formulas had a limit of time (3 years) and of language (English). One specific formula (robot AND maxillofacial surgery) was limited to 10 years (and to the English language) because of the low number of articles on this topic during the last 3 years. One formula had no limit of time (distraction osteogenesis) because there were very few articles searchable in that group. To complete the research, 96 more articles were added after selection by hand search from the US Patent Office, the European Patent Office, subject related books, and the following journals: International Journal of Computer Assisted Radiology and Surgery, Revue de Stomatologie et de Chirurgie Maxillo-faciale, American Journal of Orthodontics, Journal of Oral and Maxillofacial Surgery, Journal of Cranio-maxillofacial Surgery, European Journal of Orthodontics, American Journal of Orthodontics and Dentofacial Orthopedics, International Journal of Oral and Maxillofacial Surgery, Journal of Clinical Orthodontics, Neuroradiology, Computer Aided Surgery, International Journal of Adult Orthodontics and Orthognathic Surgery, Studies in Health Technology and Informatics, Archives of Surgery, International Journal of Oral and Maxillofacial Implants, Clinical Implant Dentistry and Related Research, Periodontology 2000, Journal of Prosthetic Dentistry, Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontology, Medical Physics, British Journal of Oral and Maxillofacial Surgery, Clinical Oral Implants Research, and Journal of Orofacial Orthopedics. Altogether, we found 1721 articles. Most of the articles (1428) were excluded based on the title and abstract and because of duplications between the nine search formulas. Finally, 292 articles were selected for the present review.

3. RESULTS

The 292 articles selected were classified into the following groups: finite element analysis (n = 18), computer-assisted surgery (n = 111), rapid prototyping models (n = 41), preoperative training simulators (n = 4), surgical guides (n = 23), image-guided navigation (n = 58), augmented reality (n = 2), video tracking (n = 1), distraction osteogenesis (n = 19), robotics (n = 8), and minimal invasive surgery (n = 7).

3. DISCUSSION

3.1. Preoperative Planning

3.1.1. Finite Element Analysis in CMF Surgery

A 3D finite element (3D FE) model of the face can be based on bones, muscles [1], skin, fat, and superficial musculoaponeurotic system reconstructed from MRI, and modeled according to anatomical, plastic, and reconstructive surgery literature [2, 3]. The FE mesh, composed of hexahedron elements, is generated through a semi-automatic procedure with an effective compromise between the detailed representation of the anatomical parts and the limitation of the computational time [2]. Nonlinear constitutive equations can be implemented in the FE model [2]. The corresponding model parameters are selected according to mechanical measurements on soft facial tissue, or are based on reasonable assumptions [2]. Model assumptions concerning tissue geometry, interactions, mechanical properties, and the boundary conditions can be

validated through comparison with experiments [2]. The calculated response of facial tissues to gravity loads, to the application of pressure inside the oral cavity and to the application of an imposed displacement shows good agreement with the data from the corresponding MRI and holographic measurements [2]. The goal of the FE models of the face in CMF surgery is to predict the postoperative facial appearance with respect to prespecified bone-remodeling plans [3], and to predict the aging process [2]. Moreover, biomechanical analysis based on FE analysis (FEA) was proposed to better understand the biomechanical mechanism of rapid maxillary expansion, which is used in modifying the shape of the maxilla in cleft palate patients [4]. In CMF traumatology, biomechanical analyses involving FEA [5] were proposed to understand the role of osteosynthesis fixation [6, 7] and to find the best possible treatment (miniplates, screws, bioresorbable plates) for different fractured sites in the CMF skeleton such as mandibular symphysis [8], mandibular angle fracture [9], orbital fractures [10, 11], and massive midface injuries with bone loss [12]. FEA could also prove useful in the future to predict the likelihood of iatrogenic fracture of the jaws after surgical removal of mandibular bone, such as that occurs when the third molar is removed, and this may allow surgeons to change their approach to tooth removal in certain cases [13]. In implantology, FEA was used to choose the best drilling technique in relation to the type of bone [14, 15]. The results of the FEA imply that the success of a sinus-augmented dental implant is heavily dependent on the implant design and the rigidity of the bone grafts [15]. Presurgical FEA was also developed to predict the motion of the craniofacial skeleton under different constraints due to different types of distractors and different spatial vectors [16, 17]. Finally, FEA was used to determine the optimum consolidation period for implant loading under forces of different directions and amounts after alveolar distraction osteogenesis [18].

3.1.2. Computer Assisted Surgery Planning

Computer-assisted surgery (CAS) planning was implemented in CMF surgery so that the complex anatomy of the patient can be understood, and that the surgical task can be improved preoperatively [19-25]. Orthognathic surgery represents an important part of CMF surgery and allows for correction of different dental and maxillofacial dysmorphoses, asymmetric faces, or craniofacial syndromes by cutting and moving the maxilla and/or the mandible according to a treatment plan. Standard orthognathic surgery planning is shown in Figure 1. This procedure can be divided into the following four steps [26, 27]:

- “A” – Clinical examination, diagnosis and treatment planning.
- “B” – Transfer of maxillary and mandibular initial position to the articulator.
- “C” – Model surgery.
- “D” – Transfer of final relative maxillary-mandibular position to the operating room (OR).

In the current system, none of these steps require computer assistance. After the clinical examination [28] (Fig 1.1 - “A1”), standard orthognathic preoperative planning begins with diagnosis and treatment planning (“A2”). The diagnosis is achieved using a two-dimensional (2D) cephalometric analysis (“A2”). The treatment is generated by associating data from the clinical examination (aesthetic aspects, gingival smile, etc),

and the occlusal examination (on plaster casts), with results from the 2D cephalometric analysis. 2D cephalometric analysis provides measurements of the maxillary and/or mandibular movements to perform during model surgery (“C”) and the operative time in relation to existing normative data or to the individual’s geometrical frame [29]. Registration of the maxillary position in relation to the skull is achieved by using a face bow (“B1”) [30]. Registration of the mandibular position in relation to the maxilla is obtained by using an occlusal wax bite positioned between the two dental arches (“B2”). The face bow is then placed in a semi-adjustable articulator (“C1”). The face bow transfers the 3D position of the maxilla into a semi-adjustable articulator [31]. A plaster cast of the maxilla is positioned on the face bow (“C2”) and fixed by plaster to the upper arm of the articulator. The occlusal bite registration is used for positioning the mandibular plaster cast relative to the maxilla. Horizontal and vertical reference lines are traced for both plaster casts (“C3”). The plaster casts are then separated from the articulator by sawing. The casts are subsequently moved by the surgeon to their final positions (“C4, c”). The amount of movement imposed to the plaster casts should theoretically correspond to that planned with the 2D cephalometric analysis. This movement may create a gap between the reference lines. The gap is measured with a manual caliper [32]. The intercuspidation plate (or splint) (“D”) represents the impression (in resin) of teeth contacts between the two dental arches. The intermediary and final maxillary positioning in relation to the mandibular plaster cast requires the manufacturing of two splints [33-35], which represent the unique element of transfer between model surgery (“C4”) and OR (“D”).

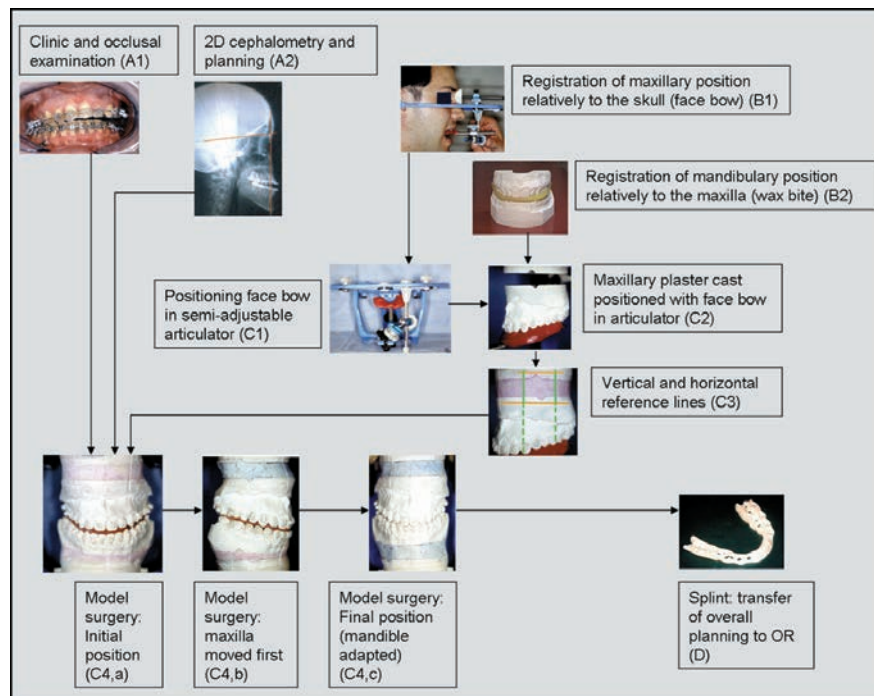


Figure 1. Standard orthognathic surgery planning.

Table 1. The pitfalls and limitations of a standard orthognathic surgical procedure.

2D radiological planning (A2) [29, 36-40]	Face-bow (B1) [26, 30, 31, 40]	Model surgery (C2-C4) [26, 40-44]	Splint (D) [33, 40]
Insufficient distance between the source and the target	Inaccuracy in the 3D positioning of the device	Hand-drawn reference lines	Resin may be deformed if heating is not achieved within the articulator
Inadequate filter application	Two clinicians required for manipulation	No standards for horizontal or vertical reference lines	High risk of destruction of the occlusal part of the models when resin is not correctly separated from the plaster casts
Superimpositions of anatomical structures	Long time for manipulation	The reference lines do not correspond to any lines from the 2D cephalometry	Splint does not transfer any absolute position of the maxilla and/or mandible in relation to the skull
Impossible to quantify right-left asymmetry		The reference lines do not correspond to any of the osteotomy lines	
		No standard for movement (translation or rotation) to perform first during manipulations of the plaster casts	
		No quantifiable control during the rotations of the plaster casts	

CAS [45] was introduced in orthognathic surgery as one of the technologies (Table 2) to resolve multiple weaknesses and pitfalls of standard procedures (Table 1) [46]. The stages of the CAS workflow process for routine 3D virtual treatment planning of orthognathic surgery are the following: (1) image acquisition for 3D virtual orthognathic surgery, (2) processing of the acquired image data to construct a 3D virtual augmented model of the patient's head [47], (3) 3D virtual diagnosis of the patient [48], (4) 3D virtual treatment planning for the orthognathic surgery, (5) 3D virtual treatment planning communication, (6) 3D splint manufacturing, (7) 3D virtual treatment planning transfer to the OR, and (8) 3D virtual treatment outcome evaluation [49]. The image acquisition and processing of data for the 3D virtual treatment planning can merge information from bone (computed tomography (CT) scan, cone beam CT) [50, 51], soft tissues [24, 52], external facial appearance [53-59], 3D photographic system [57], and dental occlusion [47, 60-63] to provide the most complete 3D virtual model of each patient [64]. Figure 2 exhibits an example of CAS planning in orthognathic surgery.

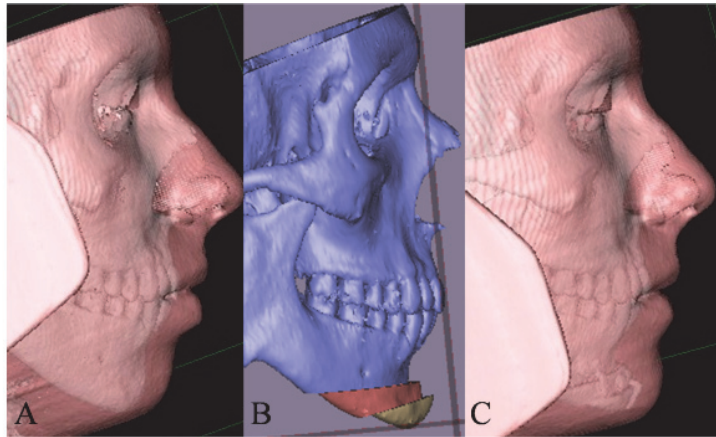


Figure 2. CAS planning in orthognathic surgery. (A) Pre-operative profile with soft and hard tissue superimposition. (B) Virtual planning with 3D cephalometric analysis and double advancement of the chin. (C) Post-operative visualisation of soft and hard tissues modification.

Table 2. Different technologies used in orthognathic surgery for the analysis, planning, and transfer of preoperative planning to OR.

Task	Means					
Analyze	2D X-Rays manual cephalometry [72-81]	2D X-Rays digital cephalometry [82]		3D cephalometry CT [83-86]		
Simulate bone movements	Articulator and plaster casts [72, 87-91]	Robot arm for model surgery [92]	3D RP model [73, 93]	CAS planning [84, 85, 94-98]		
Simulate soft tissues				CAS planning (CT, laser scan) [99-102]		
Check occlusion	Plaster casts [72, 84, 85, 87, 92]		3D CT reconstruction [63]	Laser scanned virtual model [82]	Combination 3D CT —laser scan virtual model [103]	
Transfer	Acrylic splint [72]		Surgical guide [73, 85]	Image-guided surgery [82, 84, 104-107]	Augmented reality [108]	Robotics [92, 109, 110]

Three-dimensional virtual diagnosis and treatment planning enable us to simulate and quantify osteotomies [65] and bone movements, to try to predict postoperative soft tissues appearance with a photorealistic quality [66, 67], and to verify the achievement of good postoperative virtual dental occlusion by means of collision detection algorithms [63, 68]. The movements of the mandible can be added to the 3D virtual model of the patient to provide dynamic/functional data and to predict surgical outcomes [69, 70]. In 3D virtual planning, a precise knowledge of the location of the mid-facial plane is important for the assessment of asymmetric deformities and for the planning of reconstructive procedures [69]. Automatic extraction of the mid-facial plane was proposed by De Momi et al. [71] based on matching homologous surface areas selected by the user on the left and right facial sides through iterative closest point optimization. Soft tissue prediction of the patient's final appearance after orthognathic surgery still needs some improvements [66, 67].

CAS planning in implantology allows obtaining highly precise implant positioning, taking advantage of the maximum amount of bone available, and facilitating minimally invasive surgery [111]. The workflow consists of the following steps: (1) CT/cone beam CT data acquisition [112], (2) 3D reconstruction, and (3) 3D implant planning (Implametric, Simplant [113], NobelGuide [115, 116], med 3D [117, 118]). These software allows for axial cuts and panoramic cuts with multiple bucolingual cuts. Bony and soft tissues structures can be easily visualized [114]. The tendency is toward prosthodontic-driven implant placement (Figure 3), taking into account the later prosthetic restoration [111], and to achieve integration of anatomical, biomechanical, and aesthetic factors [119]. To incorporate the information from the prosthodontic wax-up, a template is prepared and introduced into the workflow. First, a template with radioopaque position markers (gutta-percha or calibrated balls of known diameter) or a special radioopaque template (with barium sulfate coating) is made for the patient [114, 120] (Figure 3). Then the patient without the template and the template itself are separately CT scanned (Nobel guide procedure). Using the chosen software, a treatment is planned based on the implant position in the axial, sagittal and panoramic sections. The functional and aesthetic outcome will be satisfactory if the template is made based on the final shape of the tooth (shape, emergency profile, occlusion, and contact areas) and not based on bone quality alone [113]. The template can also be modified to serve as a surgical guide. If the modification of template is not possible, a new surgical guide is manufactured [113]. A different template can be used for a different supporting surface. The templates can be supported by teeth or both teeth and mucosa, or they can be directly fixed to the maxilla bone [114, 121]. The template can be stabilized by placing pins directly into the bone through soft tissue [114], raising a flap and placing the template into the bone, using wires as a guide and support [113], using transitional implants [122], or placing the template over soft tissues [114, 120]. 3D CT reconstruction enables determining the implant number, location, angle and characteristics [114]. CAS in implantology is appropriate for situations with anatomical limitations, such as an inferior alveolar nerve [120], nasal fossae or maxillary sinus [117, 123], or atrophic maxilla [119]. CAS allows visualization of the amount of available bone in each area, which is important for choosing the ideal donor site for the osseous grafts. CAS also enables choosing the best graft location as well as the shape and volume of the graft [119, 123]. In complex procedures, such as zygomatic implants

[124], 3D CAS implantology planning helps to follow the critical anatomical structures along the implant trajectory [125, 126].

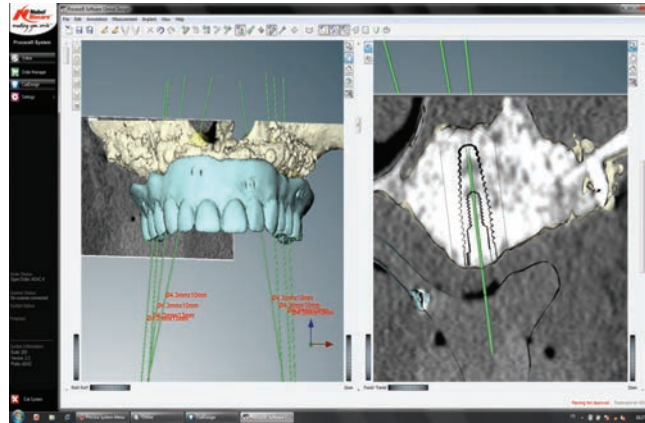


Figure 3. CAS planning in implantology. Virtual planning of 8 implants positioning in the upper maxilla after a double sinus lift, with the help of the prosthodontic-driven template (in blue).

In reconstructive oncological CMF surgery, virtual bending of the mandibular reconstructive plate [127] or shaping of the fibular graft to reconstruct the mandible after oncological resectioning can be performed by means of computer-aided design/computer-aided manufacturing (CAD/CAM) procedures [128]. CAS planning has also been used for the evaluation of the presurgical mandibular anatomy, by which 3D models of the fibula graft are obtained [128, 129].

3.1.3. Rapid Prototyping 3D Models

Rapid prototyping (RP) was introduced in the 1980's as a techniques for manufacturing of physical models from CAD/-CAM. In RP, a medical model is built layer by layer, reproducing almost every shape of the external and the internal anatomical structures (Table 3). RP models are different from the physical models manufactured by drilling [130]. The medical models or bio-models represent a part of the human anatomy at a 1:1 scale obtained from 3D medical imaging (CT scan, MRI). Fabrication of the medical models consists of four main steps: (1) 3D imaging (3D CT, MRI), (2) image processing including segmentation of the zone of interest, (3) image data optimization, and (4) construction of the medical model with RP.

Different methods have been proposed, such as stereolithography [131-135], selective laser sintering (SLS) [136, 137], PolyJet [138], fused deposition modeling [139], and 3D printing [140] (Table 3). Artifacts in 3D RP models are due to data import, computed tomography gantry distortion, metal, motion, surface roughness due to removal of support structure or surface modeling, and image data thresholding [139]. The source of the artifact can be related to the patient, to the imaging modality performance, or to the modeling technology [139]. RP medical modeling in CMF surgery involves multiple indications for diagnosis [143], instruction for residents [133], and patient information

tool when obtaining consent for surgery [134]. A specific application of RP technology is the diagnosis and treatment planning for facial fractures (i.e., titanium mesh prebent on 3D RP models to correct orbital fractures) (Figures 4, 5) [144-148].

Table 3. Different techniques of RP modeling for craniomaxillofacial surgery

Name	Technical principle	Dimensional error
Stereolithography	Photopolymer cured layer by layer with UV laser	2.2% [141] to 2.7% [142]
Selective laser sintering	CO ₂ laser beam heats powder particles and fuses them together	1.79% [138] to 2.1% [136, 138]
Fused deposition modeling	Extrusion of heated thermoplastic material layer by layer	Not found
Polyjet	Jetting a state-of-the-art photopolymer in ultrathin layers (16 μ m) onto a build tray	2.14% [138]
3D printing	Selective dispersion of binder onto powder layers	3.14% [138]

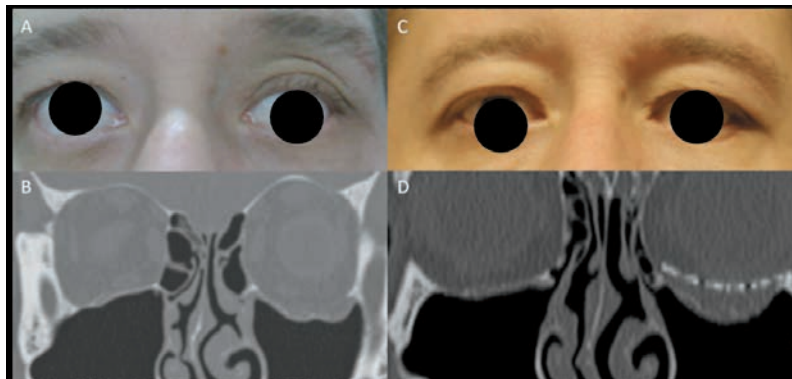


Figure 4. Rapid prototyping (RP) applied to the diagnosis and treatment planning for orbital fractures. (A) Pre-operative soft-tissue appearance for late left inferior orbital wall fracture with enophthalmos and accentuated upper palpebral fold on the left side. (B) Preoperative low-dose CT scan, coronal view, fracture of the left orbit floor. (C) Postoperative appearance of left eye; correction of the left palpebral fold. (D) Postoperative low-dose CT scan, coronal view, *restoratio ad integrum* of the left inferior orbital wall with the pre-shaped titanium mesh.

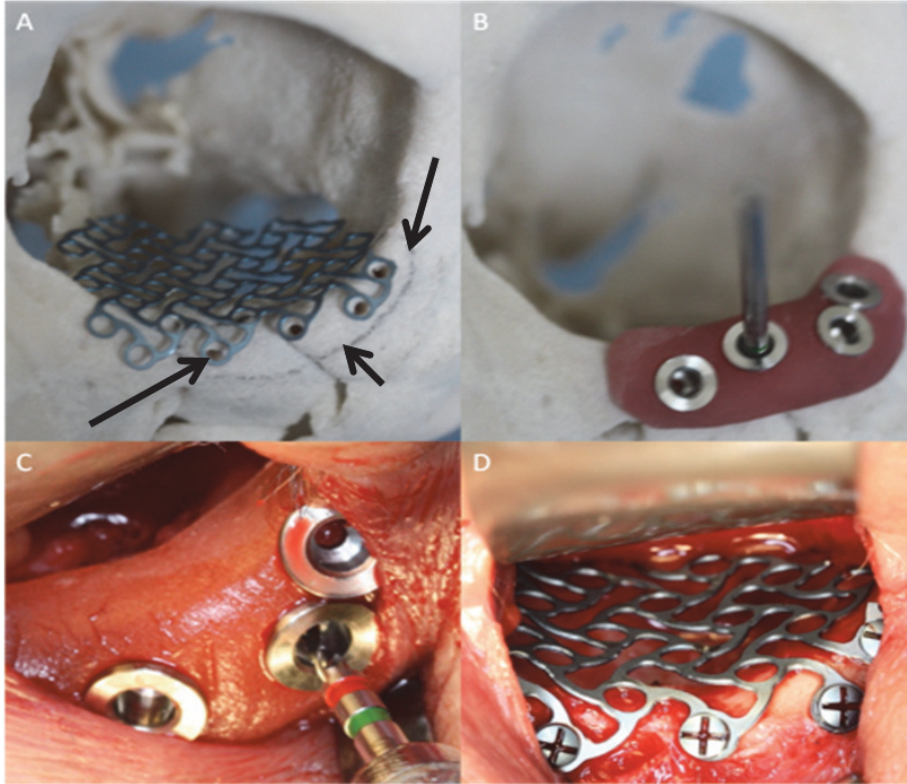


Figure 5. Rapid prototyping (RP) applied to the surgery for orbital fractures (same patient as in Figure 4). (A) Pre-bent titanium mesh on the 3D RP model. The holes for the screws and the size of the guide are marked with black pencil (arrow). (B) The acrylic surgical guide for the positioning of the holes for the screws on the 3D RP model; positioning of the drill at 90° to the bone surface. (C) Intra-operative drilling of the holes through the surgical guide. (D) Intra-operative view of the positioning of the pre-bent titanium mesh on the left orbital floor.

RP models afford manufacturing of surgical guides and splints [149] for transfer of preoperative planning (osteotomy lines, bone movements, facial asymmetry) to the operating theater in orthognathic surgery [150-152], implantology [153], and distraction osteogenesis [154-155]. In reconstructive oncological CMF surgery, 3D RP models of the fibula graft allow for choosing the best titanium plates, allow for the bending of the plates preoperatively (reducing the time spent in the operating theater [156]), and help in preoperatively planning the osteotomies and bone movements [156-160]. The 3D RP models also serve for prosthetic implant design in cranioplasty [161-166], prosthodontic rehabilitation of the midface after malignant tumor resection [167, 168] and the preparation for temporomandibular joint replacement [169, 170].

3.1.4. Preoperative Training

Very few simulators have been developed for CMF surgery, except the physical [171] or virtual [172] simulators for facial cleft palate repair and mandibular reconstruction [173]. Haptic models were added to simulate routine oral surgery procedures, such as bone drilling [174].

3.2. Intraoperative Guidance

3.2.1. Surgical Guides

In orthognathic surgery, virtual planning can be transferred to the OR with a surgical occlusal splint prepared by CAD-CAM procedures [175-177]. Olszewski et al. [178] proposed using an acrylic guide based on a 3D RP printed model for the transfer of the osteotomy lines and the screw holes for the osteosynthesis titanium plates from the preoperative orthognathic surgery planning (genioplasty) to the operating theater (Figures 6-8).

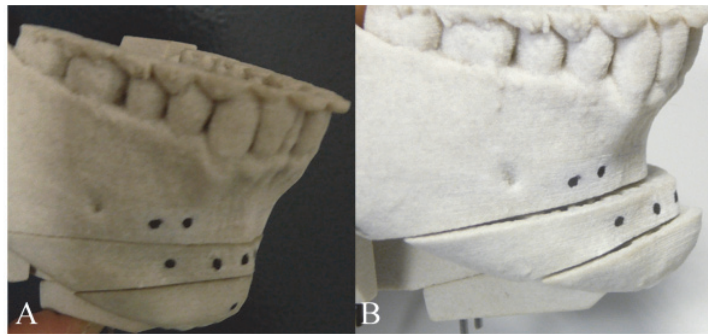


Figure 6. Surgical guide based on 3D RP printed model for the transfer from the preoperative orthognathic surgery planning to the operating theater. (A) 3D RP model, pre-operative initial position. (B) 3D RP model, postoperative final position. Black dots indicate the position of holes for the screws [178].

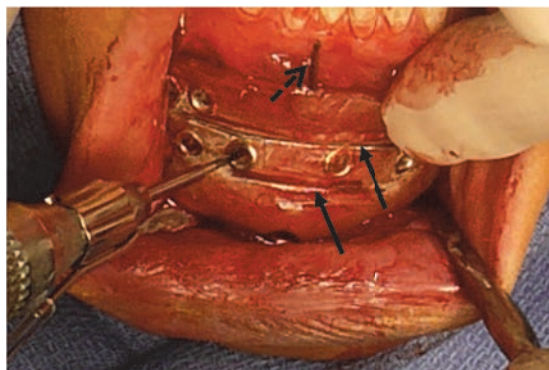


Figure 7. The acrylic guide is positioned on the osseous chin of the patient. The holes for the screws are drilled through the surgical guide. Solid arrows indicate the transfer lines for osteotomy paths. The broken arrow marks the midline indicator of the acrylic guide. The acrylic guide is fabricated on the 3D RP model based on the initial position [178].

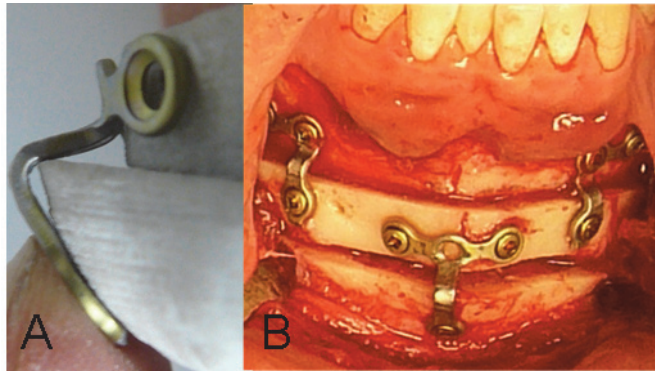


Figure 8. (A) Prebent plate on the 3D RP model in the final position. (B) Positioning and screwing of the pre-bent plates intraoperatively [178].

For CMF skull reconstruction, Clijmans et al. [179] described thin metallic templates to transfer preoperative planning of the new shape of the dysmorphic skull to the OR. In reconstructive CMF surgery, a surgical guide based on a 3D RP model is used for resectioning of the fibula and for its insertion into the resected defect on the mandible [158-160, 180, 181]. The length of the resected mandibular bone, the mandibular curvature, and the width of the basal bone can also be transferred to the fibula flap with a surgical guide [158].

In CAS implantology [191, 194], surgical guides are used to facilitate procedures such as maxillary sinus lift elevation (bone grafting of the maxillary sinus before implant placement in the maxilla) (Figure 3) [195], zygomatic implants [124] or pterygoid implant positioning [196], and placement of orbit prosthesis after orbital exenteration [197]. The advantages and disadvantages of surgical guides in implantology are summarized in Table 4.

3.2.2. Image-Guided Navigation

Image-guided navigation leads to an improvement in surgical accuracy with the aid of software that uses the images captured from CT or MRI and a tracking system for the surgical instruments [126]. The accuracy of image-guided navigation in CMF [198]

Table 4. The advantages and disadvantages of surgical guides in implantology.

Advantages	Disadvantages
Transfer of the diagnostic wax-up for a prosthodontic restoration into actual implant planning [182]	Not allowed for alveolar ridge expansion [126]
Increased precision of implant positioning [113, 183]	Conditions of mucosa not considered [184]
Increased directional precision of drilling [185, 187]	Tactile reference lost [189]
Reduced operating time [113, 188]	Precise milling depth not given [126]
Reduced surgical errors [113, 190]	Bone interference [193]
Bone and tooth support possible [114, 191, 192]	

depends on the imaging modalities [199], patient-to-image registration procedures, the navigation system used [200-202], data acquisition [94], interaction of the surgeon with the system [200], technical errors [200], and instrument tracking [203-205]. The technical accuracy and the navigation procedures seem to be of minor influence [198].

Image-guided navigation requires a means of registering anatomical points in the medical image (CT or MRI) and a software program to locate the surgical instruments [198, 206-210]. Knowing the exact position of the instrument is the key to the success of the surgical intervention. CT/MRI images are used as a map to provide the surgeon with a real-time representation of the surgical instruments in relation to the images of the patient. This real time representation allows for tracking the instrument position during the surgery and their visualization on the computer [211]. During the surgical phase, the surgeon is given interactive support with guidance in order to better control potential dangers and avoid complex anatomical regions [94, 212]. Navigation is possible through a series of sensors attached to the rotator instruments, the surgical template and a cap fixed on the patient's head, and the data are captured by different systems. The obtained data are transferred immediately to the computer and enable the surgeon to view the real situation [94].

The systems used in image-guided navigation evolved from stereotactic neurosurgical systems (mechanical) [94, 211], ultrasound-based (connected to satellite) [94], and electromagnetic systems (based on the localization of the instruments by measuring the changes produced in the magnetic field intensity) [211, 212], to optical navigation systems based on infrared light (localization of infrared light emitting diodes on the instruments captured through cameras mounted in the operation room) [211, 213-215]. StealthStation is the most accurate optical navigation system (mean [SD] target registration error: 1.00 [0.04] mm), followed by VectorVision (1.13 [0.05] mm), and then Voxim (1.34 [0.04] mm) ($P < .05$) [202].

Traumatic CMF injuries often present difficult reconstructive challenges for CMF surgeons [216, 217]. Reconstruction is often complicated by significant soft tissue loss, comminuted bone fragments, tenuous blood supply, and wound contamination [217]. For panfacial injuries, restoration of normal facial width, facial height, and sagittal projection may be difficult to achieve [217]. Marked swelling may limit the surgeon's ability to palpate and recognize subtle bony defects and malunion [217]. Furthermore, a true 3D assessment of bony alignment may not be possible with traditional surgical exposures to the craniofacial skeleton [217]. Image-guided navigation affords precise treatment of old fractured zygoma in the appropriate position and orientation [218, 219]. Intraoperative navigation can reconstruct a complex post-traumatic orbital anatomy, restore the midfacial symmetry and optimize the treatment outcome [220-222].

The association of CAS with stereolithographic models and with intraoperative navigation was applied to the planning and repair of zygomatico-orbito-maxillary complex fractures [223-225]. Intraoperative navigation in maxillofacial fracture repair facilitates reconstruction in unilateral defects through mirroring techniques, and reconstruction in bilateral defects by importing virtual models from standard CT datasets and by improving the software tools needed for maxillofacial surgical reconstruction [226-228].

Navigation can make tumor surgery more reliable by specifying the correct safety margins, protecting vital structures, and facilitating the reconstruction process [229]. Image-guided navigation is especially useful in tumor resection involving complex anatomy areas modified by tumor growth [230-232] (such as the orbit), in the proximity of cerebral structures, and when cranial nerves could be injured [233, 234]. Image-guided navigation allows for the immediate reconstruction of the unilateral resected area with an autologous graft designed and positioned under navigation with a preoperative plan based on the mirrored healthy side [235]. CAS navigation in CMF tumor resection can also be combined with new imaging modalities, such as positron emission tomography [236, 237]. In this combination, the surgeon is simultaneously provided with anatomical and functional (metabolic) details. The resulting fused images offer improved localization of malignant lesions and improve the targeting of the biopsy, especially for small lesions [236]. Reisner et al. [238] proposed the integration of spectroscopy-based biosensors with an image-guided surgery system. Their system can simultaneously provide the surgeon with information about the diagnosis of the tissue and its 3D localization. This information could help to increase the safety during surgery for malignant tumor resections [238].

In implantology, the accuracy achieved with manual implantation is sufficient [200]. However, some situations exist where a very precise navigation-guided implantation [239] is required, such as those due to anatomical limitations (inferior alveolar canal, nasopalatine canal, maxillary sinus, pterygoid region), limited space, atrophic maxillae [240-246], sinus lift, and trans-zygomatic implants [200, 247, 248]. Image-guided navigation in orthognathic surgery enables transfer of individualized 3D virtual planning and drilled screws holes for plating the osteotomy lines [249] to improve the reproducibility of the preoperative simulation [250, 251]. Intraoperative navigation has also been used in the resection of the ankylotic bone in temporomandibular joint (TMJ) gap arthroplasty [252] and for TMJ arthroscopy using optoelectronic tracking technology [253, 254].

The most difficult clinical situations for image-guided navigation in the CMF region are related to edentulous patients and to the mandible [255]. In edentulous patients, the registration depends on the required level of accuracy, the prospective region for surgical navigation, and the status of the patient's prosthesis [255]. The mobility of the mandible makes it difficult to accurately synchronize with preoperative imaging data [233]. However, a teeth-mounted sensor frame and teeth-supported fiducial markers can afford more accurate navigation for surgery of the lower jaw [233].

3.2.3. Augmented Reality

Augmented reality provides the surgeon with real-time intraoperative information from preoperative planning by see-through glasses or video projectors to directly visualize the planning data in the surgeon's field of view [256]. Mischkowski et al. [257] introduced the augmented reality tool (X-Scope) based on the visual tracking of real anatomic structures in superposition with volume-rendered CT or MRI for controlling the intraoperative translocation of the maxilla.

3.2.4. Video-tracking

Intra-operative facial nerve monitoring, which is imperative in facial nerve dissection (resection of parotid glands tumors), is based on electromyography and video-tracks the ipsilateral oral commissure displacement in relation to different levels of current administered to the nerve during surgical procedures [258].

3.2.5. Distraction Osteogenesis

Distraction osteogenesis (DO) consists of sectioning and elongating a bone at a specific rate with a distractor to create bone by osseous distraction (Figure 9). Different types of DO devices are described in Table 5. DO can reconstruct a deformed skull, a midface complex, a mandible or an alveolar ridge [259-261].

The main issue in DO is the accurate positioning of the distractor on the maxillofacial skeleton (mandible, maxilla, and cranium) [267] and the choice of the best suitable distraction vector for 3D moving and shaping of the newly created bone and soft tissues. CAS planning has been employed for individual positioning of the distractor, performing virtual osteotomies, visualizing the displacement of newly created bone in 3D space, and correcting facial asymmetries [264, 268]. Curvilinear distractors require more precise positioning and individualized patient planning based on CAS. Yeshwant et al. [269] proposed quantifying the 3D curvilinear movement to elongate the mandible by 4 parameters of movement: radius of curvature, elongation, pitch, and handedness (left- or right-turning helix). Based on these parameters, a distraction device was constructed to execute a computer-assisted plan for skeletal correction [269]. 3D CAS simulation and model surgery provide accurate orientation of the distraction vectors [131]. A combination of virtual surgical simulations and stereolithographic models can be validated as an effective method of preoperative planning for complicated maxillofacial surgery cases [170, 155, 259, 262, 270-274]. Moreover, preoperative bending of distractors on RP models [273] prevents significant loss of operation time. In DO, the 3D positioning of pins and screws affects the global movement vector and eventually affects the treatment outcome (insufficient correction of symmetry, insufficient amount of movement performed through the device) [275].

Table 5. Different types of distraction osteogenesis devices

Degree of freedom (DOF)	Intraoral	Extraoral
1 DOF	Internal trans-sinusoidal maxillary distractor [262], alveolar ridge distractor (KLS Martin Track distractor [263], smile distractor Titamed (maxillary transverse expansion), Zurich pediatric ramus distractor (KLS Martin)	Rigid external distractor (RED), Mono-block distractor (KLS Martin)
2 DOF		V2-Alveolar Distraction System; Medartis AG [264]
3 DOF	Multiaxis mandibular DO [265]	Leibinger [266]

Therefore, Kofod et al. [275] proposed transferring vector planning from 3D RP models to the operating theater through a guiding splint, while Lübbers et al. [276, 277] introduced image-guided navigation for positioning the screws during fixation of the distractor. Without navigation, the mean deviation from the planned position was 4.9 mm (varying from 0.9 to 10.7 mm), with a clear tendency to position the screws in the easy-to-access regions. With navigation, the mean deviation was significantly reduced to 1.5 mm (varying from 0.1 to 3.4 mm).

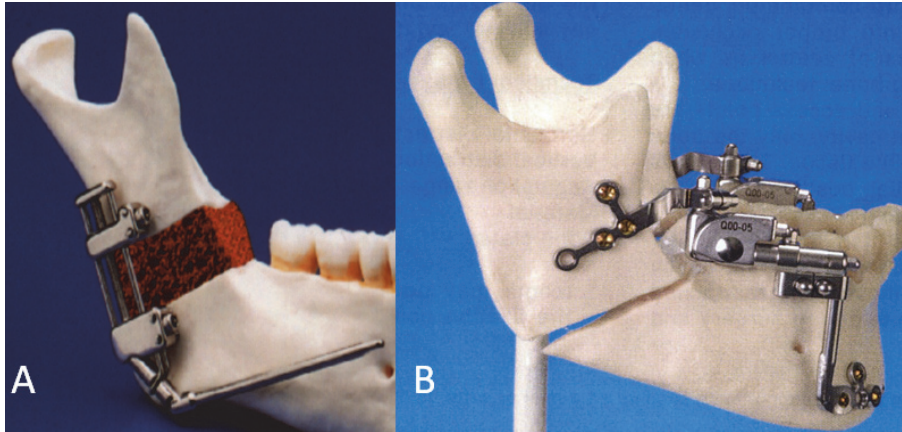


Figure 9. Internal distraction osteogenesis (DO) device with (A) 1 DOF for vertical ramus elongation, and (B) 3 DOF for horizontal ramus elongation [265].

3.2.6. Robotics in CMF

The use of robotics in CMF surgery is still limited to research institutions or large clinics, because it is difficult to implement the necessary technical and logistic measures in routine surgical work [110, 278]. The robotic system RoboDent can transfer the virtual preoperative plan for positioning the oral implants to the OR [279, 280]. This system is based on CAS navigation of the drilling system, control of the orientation of the drilling system in space, and control of the depth of drilling, through a computer-assisted interface. The absolute implant position accuracy was approximately 0.5 ± 0.4 mm, the relative accuracy between the implants was approximately 0.2 ± 0.5 mm, and the deviation from the parallel position was approximately 0.6 ± 0.5 degrees [281]. Da Vinci Surgical Robot (transoral approach) was employed in CMF surgery for the resection of the base of the tongue neoplasm in only 3 patients [282]. The application of robotics for craniotomy is confined to phantom and animal studies [283-285]. A passive robot arm was proposed by Theodossy et al. [92] to improve the model surgery phase during preoperative planning of orthognathic surgery.

3.2.7. Minimally Invasive Surgery: Endoscopic Surgery

Endoscopic surgery in CMF oncological surgery is limited to the resection of osseous tumors [286]. In orthognathic surgery, endoscopically assisted mandibular lengthening with bilateral sagittal split osteotomies and transoral osteosynthesis reduces periosteal degloving and consequent edema. However, the minimal surface available for screw osteosynthesis increases the difficulty of the procedure [287].

Frontal sinus fractures account for 5 to 15% of all maxillofacial injuries [288]. The majority of these fractures are the result of high-impact injuries such as motor vehicle accidents, assaults, and sporting events [288]. The treatment algorithm for complex frontal sinus fractures is controversial due to the associated risks of brain injury, meningitis, cerebrospinal fluid fistula, and mucocele formation [288]. However, mild to moderately displaced anterior table fractures have a relatively low risk of long-term morbidity and are generally treated as esthetic deformities [288]. Unfortunately, the coronal approach for the repair of these injuries is associated with significant sequelae including large scars, alopecia, paresthesias, and, uncommonly, facial nerve injuries [288]. These sequelae may result in greater cosmetic deformities than the initial injury. Consequently, an endoscopic approach to these injuries has recently been proposed [288]. The advantages of endoscopic surgery include limited incisions, reduced soft tissue dissection, reduced risk of alopecia, minimal risk of postoperative paresthesias, reduced hospital stay, and improved patient selection [288]. However, its disadvantages include a moderate learning curve, narrow field of view, lack of depth perception, and the fact that the surgeon cannot operate bimanually without an assistant [288].

Owing to the risk of facial nerve damage and the creation of visible scars, surgical treatment of condylar mandible fractures using an extraoral approach remains controversial [289]. The transoral endoscopically assisted approach for condylar fractures has been reported to avoid these complications [289]. Endoscope-assisted treatment has proved to be more time-consuming but may offer advantages for selected cases, particularly in reducing the occurrence of facial nerve damage [290]. The advancements in miniaturization afford new applications of endoscopy in implantology for intraoperative observations, the assessment of implant sites, and active assistance during implant placement procedures [291]. The major ducts of salivary glands have been explored with a miniaturized sialendoscope, providing a minimally invasive approach for the diagnosis and treatment of obstructive diseases and chronic infections [292].

4. CONCLUSIONS

Surgical engineering plays a fundamental role in the development and improvement of CMF surgery. The growth in importance of different technologies varies with time. Some technologies have reached maturity and have multiple clinical applications, such as CAS, image-guided navigation, and 3D RP models. Other technologies, such as augmented reality, robotics, and endoscopy require further improvements. Preoperative CAS training has been poorly developed. The existing surgical CMF simulators are in their infancy and are behind advanced pilot simulators. Joint efforts between the surgical and engineering communities should be directed toward integrated surgical simulators for training surgeons for complex surgeries, based on simulations of maxillofacial anatomy, image fusion modalities, and the haptic interface. The most

pressing issue is to establish effective communication between surgeons and engineers, so that clinical problem encountered by surgeons can be communicated to the engineers and resolved through joint efforts [293].

CONFLICT OF INTEREST: The author declares no conflict of interest.

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