Published in final edited form as:

Curr Opin Organ Transplant. 2016 October ; 21(5): 523–529. doi:10.1097/MOT.0000000000000350.

Development and refinement of computer-assisted planning and execution system for use in face-jaw-teeth transplantation to improve skeletal and dento-occlusal outcomes

Sepehr Hashemi^{a,b,c}, Mehran Armand^{c,d,e,f}, and Chad R. Gordon^{b,c,g}

^aHarvard School of Dental Medicine, Boston, Massachusetts

^bDepartment of Plastic and Reconstructive Surgery, The Johns Hopkins Hospital

^cJohns Hopkins University School of Medicine, Baltimore

^dJohns Hopkins Applied Physics Laboratory, Laurel

^eDepartment of Orthopedic Surgery, The Johns Hopkins Hospital

^fDepartment of Mechanical Engineering, Johns Hopkins University

^gDepartment of Neurosurgery, The Johns Hopkins Hospital, Baltimore, Maryland, United States

Abstract

Purpose of review—To describe the development and refinement of the computer-assisted planning and execution (CAPE) system for use in face-jaw-teeth transplants (FJTTs).

Recent findings—Although successful, some maxillofacial transplants result in suboptimal hybrid occlusion and may require subsequent surgical orthognathic revisions. Unfortunately, the use of traditional dental casts and splints pose several compromising shortcomings in the context of FJTT and hybrid occlusion. Computer-assisted surgery may overcome these challenges. Therefore, the use of computer-assisted orthognathic techniques and functional planning may prevent the need for such revisions and improve facial-skeletal outcomes.

Summary—A comprehensive CAPE system for use in FJTT was developed through a multicenter collaboration and refined using plastic models, live miniature swine surgery, and human cadaver models. The system marries preoperative surgical planning and intraoperative execution by allowing on-table navigation of the donor fragment relative to recipient cranium, and real-time reporting of patient's cephalometric measurements relative to a desired dental-skeletal outcome. FJTTs using live-animal and cadaveric models demonstrate the CAPE system to be accurate in navigation and beneficial in improving hybrid occlusion and other craniofacial outcomes. Future refinement of the CAPE system includes integration of more commonly performed orthognathic/maxillofacial procedures.

Correspondence to Chad R. Gordon, DO, FACS, Department of Plastic and Reconstructive Surgery, Johns Hopkins University School of Medicine, JHOC 8161, 601 N. Caroline Street, Baltimore, MD 21287, United States. Tel: +1 410 955 9471; cgordon@jhmi.org.

Conflicts of interest

There are no conflicts of interest.

Keywords

computer-assisted surgery; hybrid-occlusion; maxillofacial transplantation

INTRODUCTION

Despite the fact that the first face-jaw-teeth transplant (FJTT) happened almost a decade ago [1], notable technologies and innovations have already been developed to augment functional and aesthetic outcomes. For example, preoperatively, a virtual face transplant model has been developed that may help prioritize match criteria in donor-recipient pair selection [2], and numerous imaging modalities have been tested for assessment of pre-transplant perfusion for better alloflap design and prediction of viability [3–7]. Postoperatively, computed tomography (CT) imaging has been used to monitor changes in bone and nonfat soft tissue [8], image-guided procedures have been reported to diagnose and treat specific complications arising in patients having undergone face transplants [9], and a computer-assisted design and manufacturing system has been developed for orthognathic planning in FJTT [10]. Similar technology has been extensively developed, tested, and reported by Gordon *et al.* [11] and is the topic of this review. Although the use and development of computer-assisted technologies for craniofacial surgery is becoming more and more common [12–17], its implementation in the setting of FJTT is relatively novel. This review surveys the development and refinement of the computer-assisted planning and execution (CAPE) system for use specifically in FJTT and possibly other similar orthognathic endeavors.

THE COMPUTER-ASSISTED PLANNING AND EXECUTION SYSTEM FOR FACE-JAW-TEETH TRANSPLANT

The use of orthognathic principles in face-jaw-teeth transplant and aiming to optimize ‘hybrid occlusion’ sets the stage for developing a computer-assisted face-jaw-teeth transplant platform

Several successful osteocutaneous maxillofacial transplants performed to date have required some form of orthognathic revision surgery [18], which entails some risk due to posttransplant setting of immunosuppression and suboptimal perfusion. With the premise that such revisions may be preventable, emphasis was placed on using orthognathic principles (e.g., optimizing centric occlusion, intercuspatation, or freeway space in edentulous cases, and etc.), tools, and techniques to achieve optimal intraoperative bony relations prior to rigid fixation. Termed by Gordon *et al.* [19], *hybrid occlusion* refers to the occlusion formed between the donor jaw and recipient jaw after maxillofacial transplantation. It was defined as either optimal or suboptimal, with the former meeting the criteria of bilateral posterior contact, overbite/overjet less than 2 mm, and achievement of proper midline symmetry, with centric relation [20,21]. It was theorized that intraoperative optimization of both hybrid occlusion and cephalometric parameters may prevent the need for subsequent surgical revisions.

Initially, the preoperative preparation and intraoperative use of dental casts, gunning splint, and occlusal splint noticeably improved hybrid occlusion and other bony relations in cadaver model FJTTs [19,20] (Fig. 1). However, these tools posed considerable shortcomings: given that a transplant should ideally occur within 24–36 h of donor identification, fabrication of such splints was time consuming, adding up to several hours in the preoperative preparation routine, and required the labor of dental specialists (e.g., dental technician, prosthodontists, or oral/maxillofacial surgeons). Also, unexpected but often inevitable intraoperative deviations to the planned outcome rendered such dental devices obsolete due to inability to modify them. For instance, although dental devices were not used in the first face/maxilla transplant performed in 2008, they would have been obsolete regardless as all of the patient's teeth, except for the central incisors, were extracted intraoperatively due to unexpected poor oral health [19].

Inspired to resolve these limitations, development began on a CAPE system (i.e., visual tracking of donor-to-recipient relation) that allows for dynamic, real-time intraoperative optimization of not only hybrid occlusion, but also other functional and aesthetic facial-skeletal relations.

A computer-assisted planning and execution system for use in face-jaw-teeth transplant was developed

Since its first introduction 30 years ago [22], intraoperative computer-assisted surgery (CAS) and navigation has been gaining clinical traction for oral/maxillofacial applications [12,23–25]. However, unique challenges faced in FJTT required design of a seamless CAPE system specifically designed for FJTT. Furthermore, rather than planning virtually in one system and then confirming success of donor segment positioning with another program, the goal was to create one comprehensive platform. Therefore, a CAPE system was developed in 2011 by a multidisciplinary collaboration between the Johns Hopkins University School of Medicine Department of Plastic and Reconstructive Surgery, the Johns Hopkins University Applied Physics Laboratory, and the Walter Reed National Medical Center 3D Medical Center.

The fundamental paradigm of the system involves preoperative development of a surgical plan, intraoperative registration of the plan to the patient, and implementation of the plan using CAS navigation [11]. To that end, a real-time intraoperative navigation system with color-change confirmation, termed real-time cephalometry (RTC), was also developed as a part of the CAPE system.

During the preoperative phase, obtained CT scans are used in MIMICS (Materialise, Leuven, Belgium) to design and subsequently manufacture stereolithographic three-dimensional models of the recipient, donor, and the predicted postoperative result, which may be used by the surgical team to review and modify the planned treatment. Dolphin 3D Imaging (Dolphin Imaging & Management Solutions, Chatsworth, California, USA) may also be used to analyze the recipient and donor cephalometric relations for further surgical planning. Once planned posttransplant outcomes are finalized, 'Snap-On' surgical donor and recipient cutting guides with reference geometries are designed (and manufactured with eyelets for intraoperative screw fixation), and ideal posttransplant cephalometric values are

noted. Lastly, cranial references (novel kinematic references mounted to three intermedullary fixation or IMF screws), which can be used to track the cutting guide sensors using an optical tracker (Polaris, NDI Inc., Waterloo, Ontario, Canada), are also fabricated.

Intraoperatively, the dissected recipient and the donor skulls are digitally registered in separate workstations by an optical tracker that relates a digitizer to rigidly fixed intracranial sensors. To register, the surgeon first digitizes three bony landmarks for initial registration of prepared virtual model to the actual anatomy and then uses the digitizer to collect many points from of the exposed bone, whereas the CAPE system refines the registration using an iterative closest point registration technique [26].

Subsequently, the cutting guides are firmly placed using self-drilling screws (Fig. 2), and appropriate osteotomies ensue. Once the donor alloflap has been harvested, onscreen navigation will allow guided onset placement using facial-skeletal visualization and real-time quantitative cephalometric reporting (i.e., RTC) of the hybrid anatomy. This allows optimization of bony relations, especially in the event of any unexpected deviations from the original surgical plan (Fig. 3).

A live, translational miniature swine model was developed for computer-assisted planning and execution system testing

Trial of the CAPE platform required a practical experimental model, and a miniature swine model provided the best compromise of size, live clinical assessment, and human homology. This model offers large enough anatomy in which surgical cutting guides and sensors may be rigidly fixated. Furthermore, unlike cadaver models, this model avoids the mobility limitations imposed by masticatory rigor mortis and allows for clinical follow-up of both form and function. Also, the applicability of swine cephalometric markers to human was already validated for complicated craniofacial osteotomies [27,28].

However, a major challenge in developing a swine model was determining optimal muscle attachment sites on the recipient jaw, which requires understanding of swine mastication and bite mechanics. To overcome this challenge, an inverse dynamics swine mastication model was developed in which muscle activations/forces can be calculated from a desired mandibular motion and temporomandibular joint (TMJ) reaction forces. This model allows identification of muscle attachments in which the masticatory muscle activation and TMJ forces are minimized for a specific masticatory function or chewing motion. Once developed, this model had a mean absolute error (MAE) of less than 0.08 between the predicted and measured activation levels of all muscles, and MAE of less than 7 N for TMJ reaction forces between the predicted and measured [29]. This accuracy was acceptable for use in the FJTT swine model.

Initial swine FJTTs ($n = 2$) proved the CAPE system to be both successful and beneficial, especially in compensating for donor-recipient size-mismatch discrepancies. Preparing the CAPE system for operation (e.g., attaching references, performing registration, and attaching cutting guides) added about 11 min to the length of the FJTT. The registration error was 0.6 (SD, 0.24) mm [11].

Cephalometric landmarks for intraoperative real-time cephalometric face-jaw-teeth transplant assistance were established and validated using the swine model [30]

The system's intraoperative navigation module reports translation of anatomical positions, which may be represented by cephalometric landmarks. Such landmarks must be translatable onto the human facial skeleton; remain stable throughout surgical anatomical manipulations; not be on lines of osteotomy; and be viable regardless of age, sex, and size of either the recipient or the donor. Given the strong homology of the swine model to humans, swine FJTTs were used to experiment and validate candidate landmarks.

Two swines underwent Le Fort-III-based alloflap harvest and autoreplantation with rigid fixation ($n = 2$) and two pairs of size-mismatched swines underwent Le Fort-I-based allotransplantation ($n = 2$), where in both pairs the larger maxillofacial alloflap was transplanted onto a smaller recipient to imitate a common limitation faced by transplant teams. Dolphin 3D was used for postoperative cephalometric analysis, with an emphasis on the posttransplant hybrid occlusions.

Throughout all transplants, several of the chosen landmarks met the described criteria. These landmarks shared strong homology with the human cranium, were readily identifiable both preoperatively (in imaging) and intraoperatively (using computer-aided surgical navigation), and were also conserved throughout the transplant, allowing for reliable cephalometric analysis. The stability and functionality of these landmarks and measurements established their use for future transplants. Using these landmarks, many cephalometric measurements were selected for use by the CAPE system (Table 1).

The computer-assisted planning and execution system was implemented and optimized in human cadavers

Initially, numerous unpublished mock FJTTs were performed on plastic models fabricated using CT data of live swine or cadavers. Although less challenging than live-animal FJTTs, the mock FJTTs allowed for several realizations: first, donor fragment attachment to recipient in the human scenario is more difficult than in the swine model due to having three planes of osteotomy, as opposed to one. This challenge may be alleviated by temporary, reversible fixation using a novel locking mechanism prior to rigid fixation. Lastly, the curvatures of the human skull and swine skull are different, and cranial references designed for the swine skull would not fully attach to the human skull. This was fixed by redesigning the cranial reference angulation. Registration errors for recorded human plastic model FJTTs were 0.727 and 0.306mm for the human donor and recipient, respectively, comparing with 0.510 and 0.357 mm for the swine donor and recipient, respectively.

Cadaveric FJTTs ensued the mock FJTTs on plastic models and, as expected, had a higher registration error (1.22 and 0.745 mm for the cadaver donor and recipient, respectively). The mean navigation error, measured by comparing postoperative CT scans with intraoperative measurements by RTC, was 3.59 mm for the cadaver model, in comparison with the plastic model FJTTs, which did not exceed 1.250 mm. This increase in navigation error was likely due to the increased registration error (e.g., 0.98 vs. 0.52 mm in cadaver vs. human plastic skull studies), perhaps caused by residual soft and connective tissue irregularities on the

cadavers [18[■]]. Regardless of the error, the intraoperative navigation was beneficial in preventing ‘surgeon error’ and confirming correct positioning and attachment of the cutting guide. The latter was especially helpful, as previous studies had reported some error in the accuracy of the manufacturing process and attachment of the cutting guides [11]. Lastly, preoperative planning for the CAPE system was typically completed within 5 h, whereas printing the instruments was an overnight ‘set-and-forget’ process.

Regardless of successful translation to cadaver models, the error was too high to be acceptable. Ergo, further plastic skull and human cadaveric studies were conducted for refinement of the RTC module. In one series, mean navigation error for various cephalometric parameters was 1.06 ± 0.63 mm and 0.53 ± 0.39 degrees for the plastic skull FJTT, and 1.39 ± 1.81 mm and 2.18 ± 1.88 degrees for human cadaver study [21[■]], demonstrating increased accuracy relative to the previous studies. Of note, error was also observed in cephalometric parameters that should have shown zero change as they were not manipulated at all by the surgical plan. These measures, purposefully chosen as controls prior to the FJTT, prove existence of interobserver/intraobserver error (e.g., imprecise landmark placement for measurement of cephalometric data) and/or varying imaging precision (i.e., CT parameters). This suggests that the actual navigation error is smaller than perceived, as it was not adjusted for observer error.

Although the navigation error may be reduced further, its current accuracy is clinically acceptable and reliable. A different source of error that may impair transplant outcomes, however, is error from the preoperative planning and the design of the surgical cutting guides. This is often the case with nonexistent or partial CT imaging that may no longer be obtainable or repeatable due to irreversible trauma or the time constraints of transplantation after donor identification. Although in early stages, approaches are being investigated in extrapolating missing digital anatomy [31]. Such algorithms provide easier and more accurate preoperative design of surgical guides, prosthetic anatomy, and surgical planning.

Future plans for further development of the CAPE system for FJTTs include development of vessel and nerve navigation, further refinement of both registration and intraoperative navigation accuracy, and development of more capable preoperative surgical-planning software. In addition, refined hardware designs shall allow for increased scope and applicability of this patent-pending technology in standard cases involving common orthognathic and craniofacial surgical procedures.

Restoring donor face posttransplant [32]

Although FJTTs or ‘face transplants’ carry heavy social and psychological burden for the recipient due to perceived manipulation of identity, the donor family may also be affected by ‘identity loss’ of their lost loved one. Therefore, current protocols for facial transplantation appropriately require mandatory fabrication of a mask that properly conceals donor dissection.

Early in FJTT protocol development, colored acrylic resin and silicone masks were produced, which required obtaining alginate impression of the donor face, a process that

takes about 4h for production. This technique results in a detailed mask that may be used for open casket burial.

With the advent of additive manufacturing, more novel technologies are also being used. Additive manufacturing production of a face mask requires three-dimensional surface data collection (e.g., CT, three-dimensional photography, three-dimensional scanning, or etc.) and a color photo of the donor. Upon obtaining these data, the mask itself can be produced via Direct Binder Jetting, Indirect Binder Jetting, Materials Jetting, or Sheet Lamination. These techniques all require variable time and financial resources, which may be decided depending on the needs of the donor family.

CONCLUSION

FJTT is a complex procedure that presents unique surgical challenges. Development of a CAPE system that complements the surgeon's arsenal in optimizing posttransplant functional and aesthetic outcomes, all the while reducing surgical time and unexpected decision-making, is beneficial. From its development using mock transplants on plastic models, to swine model, and human cadaver models, the presented CAPE system has proven to be an accurate and useful CAS platform in Le Fort-based, maxillofacial surgery. Similarly, future research in developing a related platform - known as craniofacial surgical assistance workstation - will help to improve outcomes in cranioplasty reconstruction with patient-specific implants.

Acknowledgements

We would like to acknowledge that the following team members be considered as coauthors of this article - Ryan Murphy, PhD; Kevin Wolfe, PhD; Gerald Grant, DMD, MS; and Peter Liacouras, PhD.

Financial support and sponsorship

None.

REFERENCES AND RECOMMENDED READING

Papers of particular interest, published within the annual period of review, have been highlighted as:

■ of special interest

■ of outstanding interest

1. Alam DS, Papay F, Djohan R, et al. The technical and anatomical aspects of the World's first near-total human face and maxilla transplant. *Arch Facial Plast Surg* 2009; 11:369–377. [PubMed: 19917898]
2. Wallins JS, Chandawarkar AA, Dobry A, et al. Craniofacial measurements of donors and recipients correlate with aesthetic outcome in virtual face transplantation. *Plast Reconstr Surg Glob Open* 2015; 3:e385. [PubMed: 26090275] ■ This study used a relatively large number of virtual face transplants to validate a set of craniofacial measurements studied for improving aesthetic outcomes.
3. Soga S, Pomahac B, Mitsouras D, et al. Preoperative vascular mapping for facial allotransplantation: four-dimensional computed tomographic angiography versus magnetic resonance angiography. *Plast Reconstr Surg* 2011; 128:883–891. [PubMed: 21921764]

4. Nguyen JT, Ashitate Y, Buchanan IA, et al. Face transplant perfusion assessment using near-infrared fluorescence imaging. *J Surg Res* 2012; 177:e83–e88. [PubMed: 22572616]
5. Nguyen JT, Ashitate Y, Venugopal V, et al. Near-infrared imaging of face transplants: are both pedicles necessary? *J Surg Res* 2013; 184:714–721. [PubMed: 23706565]
6. Sisk GC, Kumamaru KK, Schultz K, et al. Cine computed tomography angiography evaluation of blood flow for full face transplant surgical planning. *Eplasty* 2012; 12:e57. [PubMed: 23308304]
7. Soga S, Wake N, Bueno EM, et al. Noninvasive vascular images for face transplant surgical planning. *Eplasty* 2011; 11:e51. [PubMed: 22184509]
8. Kueckelhaus M, Turk M, Kumamaru KK, et al. Transformation of face transplants: volumetric and morphologic graft changes resemble aging after facial allotransplantation. *Am J Transplant* 2016; 16:968–978. [PubMed: 26639618]
9. Lee TC, Chansakul T, Huang RY, et al. Early postoperative imaging and image-guided procedures on patients with face transplants. *AJNR Am J Neuroradiol* 2015; 36:568–574. [PubMed: 25339651]
10. Dorafshar AH, Brazio PS, Munding GS, et al. Found in space: computer-assisted orthognathic alignment of a total face allograft in six degrees of freedom. *J Oral Maxillofac Surg* 2014; 72:1788–1800. [PubMed: 24656428]
11. Gordon CR, Murphy RJ, Coon D, et al. Preliminary development of a workstation for craniomaxillofacial surgical procedures: introducing a computer-assisted planning and execution system. *J Craniofac Surg* 2014; 25:273–283. [PubMed: 24406592]
12. Hassfeld S, Muhling J. Computer assisted oral and maxillofacial surgery - a review and an assessment of technology. *Int J Oral Maxillofac Surg* 2001; 30:2–13. [PubMed: 11289616]
13. Edwards SP. Computer-assisted craniomaxillofacial surgery. *Oral Maxillofac Surg Clin North Am* 2010; 22:117–134. [PubMed: 20159482]
14. Markiewicz MR, Bell RB. Modern concepts in computer-assisted craniomaxillofacial reconstruction. *Curr Opin Otolaryngol Head Neck Surg* 2011; 19:295–301. [PubMed: 21900856]
15. Rodby KA, Turin S, Jacobs RJ, et al. Advances in oncologic head and neck reconstruction: systematic review and future considerations of virtual surgical planning and computer aided design/computer aided modeling. *J Plast Reconstr Aesthet Surg* 2014; 67:1171–1185. [PubMed: 24880575]
16. Wan KH, Chong KK, Young AL. The role of computer-assisted technology in post-traumatic orbital reconstruction: a PRISMA-driven systematic review. *Sci Rep* 2015; 5:17914. [PubMed: 26643191]
17. Hsu SS, Gateno J, Bell RB, et al. Accuracy of a computer-aided surgical simulation protocol for orthognathic surgery: a prospective multicenter study. *J Oral Maxillofac Surg* 2013; 71:128–142. [PubMed: 22695016]
18. Murphy RJ, Gordon CR, Basafa E, et al. Computer-assisted, Le Fort-based, face-jaw-teeth transplantation: a pilot study on system feasibility and translational assessment. *Int J Comput Assist Radiol Surg* 2015; 10:1117–1126. [PubMed: 25230895] ■ This study marked the translation of the computer-assisted planning and execution (CAPE) system from the swine model to the human anatomy.
19. Gordon CR, Susarla SM, Peacock ZS, et al. Osteocutaneous maxillofacial allotransplantation: lessons learned from a novel cadaver study applying orthognathic principles and practice. *Plast Reconstr Surg* 2011; 128:465e–479e.
20. Gordon CR, Susarla SM, Peacock ZS, et al. Le Fort-based maxillofacial transplantation: current state of the art and a refined technique using orthognathic applications. *J Craniofac Surg* 2012; 23:81–87. [PubMed: 22337380]
21. Murphy RJ, Basafa E, Hashemi S, et al. Optimizing hybrid occlusion in face-jaw-teeth transplantation: a preliminary assessment of real-time cephalometry as part of the computer-assisted planning and execution workstation for craniomaxillofacial surgery. *Plast Reconstr Surg* 2015; 136:350–362. [PubMed: 26218382] ■■ This publication outlines the details and use of specific cephalometric measures and also includes a supplemental video content demonstrating the entire intraoperative CAPE system process using a human cadaver model. The experiments in this study validated the accuracy of the CAPE system for use in a human cadaver model.

22. Cutting C, Bookstein FL, Grayson B, et al. Three-dimensional computer-assisted design of craniofacial surgical procedures: optimization and interaction with cephalometric and CT-based models. *Plast Reconstr Surg* 1986; 77:877–887. [PubMed: 3714886]
23. Bell RB. Computer planning and intraoperative navigation in orthognathic surgery. *J Oral Maxillofac Surg* 2011; 69:592–605. [PubMed: 21353924]
24. Zinser MJ, Sailer HF, Ritter L, et al. A paradigm shift in orthognathic surgery? A comparison of navigation, computer-aided designed/computer-aided manufactured splints, and “classic” intermaxillary splints to surgical transfer of virtual orthognathic planning. *J Oral Maxillofac Surg* 2013; 71:2151.e1–2151.e21. [PubMed: 24237776]
25. Hamilton T, Markiewicz MR, Jarman J, et al. Dental outcomes in computer-assisted orthognathic surgery. *J Craniofac Surg* 2012; 23:e223–e226. [PubMed: 22627440]
26. Lavallee S, Troccaz J, Sautot P, et al. Computer-assisted spinal surgery using anatomy-based registration In: Taylor RH, Lavallee S, Burdea G, Mosges R, editors. *Computer-Integrated Surgery*. Cambridge, MA: MIT Press; 1996 pp. 425–449.
27. Farkas LG, Munro IR, Vanderby BM. Quantitative assessment of the morphology of the pig’s head used as a model in surgical experimentation. Part 1: Methods of measurements. *Can J Comp Med* 1976; 40:397–403. [PubMed: 1000401]
28. Farkas LG, James JS, Vanderby BM. Quantitative assessment of the morphology of the pig’s head used as a model in surgical experimentation. Part 2: Results of measurements. *Can J Comp Med* 1977; 41:455–459. [PubMed: 922561]
29. Basafa E, Murphy RJ, Gordon CR, et al. Modeling the biomechanics of swine mastication - an inverse dynamics approach. *J Biomech* 2014; 47:26262632.
30. Santiago GF, Susarla SM, Al Rakan M, et al. Establishing cephalometric landmarks for the translational study of Le Fort-based facial transplantation in swine: enhanced applications using computer-assisted surgery and custom cutting guides. *Plast Reconstr Surg* 2014; 133:1138–1151. [PubMed: 24445879]
31. Grupp RB, Chiang H, Otake Y, et al. Smooth extrapolation of unknown anatomy via statistical shape models. 2015; Proc. SPIE 9415, Medical Imaging 2015: Image-Guided Procedures, Robotic Interventions, and Modeling, 941524, 18 March 2015; doi:10.1117/12.2081310.
32. Grant GT, Liacouras P, Santiago GF, et al. Restoration of the donor face after facial allotransplantation: digital manufacturing techniques. *Ann Plast Surg* 2014; 72:720–724. [PubMed: 24835867]

KEY POINTS

- The use of orthognathic principles can improve outcomes in face-jaw-teeth transplants (FJTTs) - perhaps minimizing donor-to-recipient anatomical discrepancies and preventing the need for surgical revisions posttransplant.
- The computer-assisted surgery method is a novel and excellent approach to implement orthognathic principles in FJTTs.
- A comprehensive computer-assisted planning and execution (CAPE) system was first developed and tested in plastic models, refined within a live miniature swine surgery model, and then validated within a human cadaver model.
- The CAPE system is accurate and beneficial for use in FJTTs, especially in the event of deviation from original operative plan.

FIGURE 1. Initial use of dental cast models and splints to improve the hybrid occlusion outcomes in face-jaw-teeth transplant. Figure taken with permission from [19].

FIGURE 2.

The recipient cadaver after attachment of the cutting guide/trackable geometry apparatus and the cranial reference. Figure taken with permission from [21 ■■].

FIGURE 3.

Overview of the intraoperative workstations as part of the computer-assisted planning and execution system's realtime cephalometry module. Figure taken with permission from [21 ■■].

Cephalometric measurements used for preoperative planning and intraoperative planning as a part of the computer-assisted planning and execution system

Table 1.

Measurement type	Landmark measurement	Landmark/measurement abbreviation	Cephalometric significance	Purpose in studies
Distance	Gonion to B-Point	Go_B	Control	Aesthetic/function parameter
	Gonion to Menton	Go_Me		
	Sella to Nasion	S_Na		
	Zygoma to Zygoma	Zy_Zy		
	Opisthion to Nasion	Op_Na		
	Overjet	OJ		
	Overbite	OB		
	B-Point to A-Point	B_A		
	Sella to A-Point	S_A		
	Sella to Rhinion	S_R		
	Opisthion to Rhinion	Op_R		
	LAFH: Menton to ANS	Me_ANS		
	TAFH: Menton to Nasion	Me_Na		
	Ratio of LAFH to TAFH	Me_ANS/Me_Na		
Angle	A-Point-Nasion-B-Point	ANB	Facial projection; orthognathic skeletal relationship	Mandibular projection; orthognathic skeletal relation Maxillary projection; orthognathic skeletal relation
	B-Point-Sella-A-Point	BSA		
	Sella-Nasion-B-Point	SNB		
	Sella-Nasion-A-Point	SNA		

ANS, anterior nasal spine; LAFH, lower anterior facial height; TAFH, total anterior facial height. Table taken with permission from [21].