HHS Public Access
Author manuscript
Int J Comput Assist Radiol Surg. Author manuscript; available in PMC 2015 July 03.

Published in final edited form as:
Int J Comput Assist Radiol Surg. 2015 July ; 10(7): 1117–1126. doi:10.1007/s11548-014-1114-9.

Computer-assisted, Le Fort-based, face–jaw–teeth transplantation: a pilot study on system feasiblity and translational assessment

Ryan J. Murphy,
Research and Exploratory Development Department, Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA

Chad R. Gordon,
Department of Plastic and Reconstructive Surgery, Johns Hopkins University School of Medicine, Baltimore, MD, USA

Ehsan Basafa,
Department of Mechanical Engineering, Johns Hopkins University, Baltimore, MD, USA

Peter Liacouras,
3D Medical Applications Center, Walter Reed Naval Memorial Medical Center, Bethesda, MD, USA

Gerald T. Grant, and
3D Medical Applications Center, Walter Reed Naval Memorial Medical Center, Bethesda, MD, USA

Mehran Armand
Research and Exploratory Development Department, Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA

Mehran Armand: Mehran.Armand@jhuapl.edu

Abstract

Purpose—Le Fort-based face–jaw–teeth transplantation (FJTT) attempts to marry bone and teeth geometry of size-mismatched face–jaw–teeth segments to restore function and form due to severe mid-facial trauma. Recent development of a computer-assisted planning and execution (CAPE) system for Le Fort-based FJTT in a pre-clinical swine model offers preoperative planning, and intraoperative navigation. This paper addresses the translation of the CAPE system to human anatomy and presents accuracy results.

Correspondence to: Mehran Armand, `Mehran.Armand@jhuapl.edu`.

The views expressed in this article are those of the authors and do not necessarily reflect the official policy, position, or endorsement of the Department of the Navy, Army, Department of Defense, nor the U.S. Government.

Conflict of interest The authors declare that they have no conflict of interest.

Ethical standard The manuscript does not contain clinical studies or patient data and an approval by an ethics committee was not applicable. All human cadaver specimens were donated and prepared in accordance with the bylaws presented by the Maryland State Anatomy Board.

Methods—Single-jaw, Le Fort-based FJTTs were performed on plastic models, one swine and one human, and on a human cadaver. Preoperative planning defined the goal placement of the donor's Le Fort-based FJTT segment on the recipient. Patient-specific navigated cutting guides helped achieve planned osteotomies. Intraoperative cutting guide and donor fragment placement were compared with postoperative computed tomography (CT) data and the preoperative plan.

Results—Intraoperative measurement error with respect to postoperative CT was less than 1.25 mm for both mock transplants and 3.59 mm for the human cadaver scenario. Donor fragment placement (as compared to the planned position) was less accurate for the human model test case (2.91 mm) compared with the swine test (2.25 mm) and human cadaver (2.26 mm).

Conclusion—The results indicate the viability of the CAPE system for assisting with Le Fort-based FJTT and demonstrate the potential in human surgery. This system offers a new path forward to achieving improved outcomes in Le Fort-based FJTT and can be modified to assist with a variety of other surgeries involving the head, neck, face, jaws and teeth.

Keywords

Face–jaw–teeth transplantation; Face transplant; Le Fort-based transplant; Surgical cutting guide; Navigation; Preoperative planning

Introduction

Le Fort-based face–jaw–teeth transplantation (FJTT) is an emerging alternative for reconstructing patients with severe craniomaxillofacial (CMF) disfigurements non-amenable to conventional methods of reconstruction [1–4]. The experimental procedure utilizes both hard and soft tissue from a brain-dead cadaveric donor to replace damaged portions of a recipient's face, analogous to solid organ transplant. Recipient trauma sources have included ballistic wounds, blunt trauma, cancer, and animal attack [3–7]. Each combination of size-mismatched, donor and recipient anatomy presents unique challenges for both optimal function and appearance. To date, only ten Le Fort-based FJTTs (those face–jaw–teeth transplants which include the underlying facial skeletal structures such as zygomas, maxillae, orbital floors, palate, and teeth) have been performed worldwide [4]. While deemed successful, all single-jaw transplant patients have required some form of revision surgery after undergoing FJTT due to suboptimal donor-to-recipient dental alignment. Preliminary evidence suggests accurate dento-skeletal alignment in FJTT, including hybrid occlusion for opposing dental arches, is a very difficult part of this surgery [1,3,4,6,8]. As such, Le Fort-based FJTT will remain limited until this particular obstacle can be overcome.

Computer-assisted surgery (CAS) leverages patient models for preoperative planning and intraoperative navigation, guidance, and (possibly) real-time plan updates [9,10]. Many surgical procedures within similar fields like CMF surgery, head and neck surgery, ear/nose/throat (ENT) surgery, and neurosurgery have seen advances through CAS [11–15]. Recent developments in additive manufacturing technology (AMT), more commonly known as 3D printing, have enabled the use of patient-specific guides in a variety of dental and craniofacial procedures [11,14,16–18]. Accordingly, the combination of these paradigms may have extensive use in Le Fort-based FJTT and other orthognathic procedures, through more appropriate dento-facial-skeletal alignment and surgical accuracy resulting in improved outcomes.

Recent research describes a computer-assisted planning and execution (CAPE) workstation for assisting surgeons during Le Fort-based FJTT [19,20]. The goal was to develop a system that combines preoperative planning with intraoperative navigation and biomechanical guidance using patient-specific surgical cutting guides and optical navigation. This system should include unique features including real-time, intraoperative cephalometric analysis and preoperative biomechanical simulation for predicting donor-to-recipient jaw relation/motion post-transplant [21]. It is notable that the current state of the art commercial systems (e.g., Stryker Craniomaxillofacial, Stryker, Kalamazoo, MI, USA; Synthes Craniomaxillofacial, Synthes, West Chester, PA, USA) and reported (noncommercialized) systems in literature [8,11, 22] do *not* have the full suite of features developed for the CAPE system. The synthesis of these diverse features within the CAPE system may offer potential to improve accuracy and reduce operating times (reported FJTT transplant times exceed 14–30 h) over existing systems, which may lead to better patient outcomes and potentially prevent the need for revision surgery.

The pre-clinical CAPE system was initially developed and tested on swine (both cadaveric and live), without incorporating human anatomy from 3D plastic models or cadavers [19,20,23]. As such, this paper addresses the translational capabilities of the CAPE system as applied to human anatomy through mock transplants performed on human plastic models and a single-human cadaver transplant. Moreover, comparison of planned osteotomies and placement of the donor fragment identified the intraoperative accuracy of the CAPE system with respect to postoperative imaging data. A discussion on the results concludes the paper, remarking on the potential for the CAPE system to be used for Le Fort-based FJTT.

Materials and methods

System overview

The CAPE system, fully described by Gordon et al., provides planning and navigation for Le Fort-based FJTT [20]. This overview focuses on a single-jaw–teeth transplant to also address the more challenging problem of hybrid occlusion (i.e., improper teeth alignment and contact). Hybrid occlusion does *not* exist for those facial transplants (1) containing only soft tissue components and (2) containing both upper and lower jaw/teeth segments from the donor. The procedure varies slightly for different transplant routines depending on the extent of the recipient's disfigurement, but the majority of steps are consistent between surgeries for all single-jaw, Le Fort-based maxillofacial transplants.

Prior to surgery, a cadaveric donor is identified for a specific recipient in need of maxillofacial restoration. Once identified, the donor face should be harvested and transplanted within 48–72 h. Standard computed tomography (CT) scans of the donor and recipient are acquired. Segmentation of the CT data defines a set of three-dimensional volumes and surface models of relevant skeletal anatomy, which includes the cranium, upper jaw (maxilla), lower jaw (mandible), and teeth. The surface models provide visualization throughout the surgery and are the main components in the planning stage.

The donor and recipient models and CT data are manually aligned based on the type and extent of surgery, and expected osteotomy pattern (Fig. 1). For patients requiring single-jaw restoration, the surgeon's main focus is on achieving rigid, stable alignment of the cranium, jaw, and teeth; this includes analysis of the hybrid occlusion to ensure appropriate alignment. (The skeletal alignment dictates the final position of the overlying facial soft tissues—skin, muscle, and fat—and ultimate appearance.) The bony alignment of the models provides a common coordinate frame between the donor and recipient. Once aligned, the surgical team plans the surgery by identifying appropriate cutting planes on the recipient based on anthropometric differences [19]. These cutting planes are based on the type of surgery necessary (i.e., Le Fort I, II, or III) and generally follow predictable fracture patterns of the face. Curved cuts, while possible, will not follow these natural fracture patterns exhibited in the face and are more difficult to perform. The alignment of the donor and recipient models facilitates the transfer of the cutting planes identified on the recipient to analogous positions on the donor.

After identifying the goal cutting planes preoperatively, patient-specific cutting guides are designed and fabricated. The form-fitting cutting guides offer a precise fit to the bone and ensure the surgical cuts are performed at the appropriate location and angle. Integrated in the design of the geometry of the cutting guide is a rigid structure for optical tracking that does not interfere with the surgeon's cutting routine. Patient-specific guides are fabricated with the appropriate AMT processes for surgery (Fig. 2).

The initial surgical routine is identical for both the donor and recipient. First, a reference geometry is attached to the cranium. The reference geometry is visible to the optical tracker (Polaris, NDI Inc., Waterloo, Canada) and provides a static frame on the patient. A pointing tool digitizes a set of anatomical landmarks on the patient that were previously selected on CT scans (e.g., the most inferior/anterior point on the infraorbital rim and bridge of the nose for humans) to define a gross registration between the patient and the segmented surface model. Tracing the pointing tool along the exposed bone provides input to an iterative closest point [24] algorithm to obtain a more precise registration between the patient and the model. The cutting guides are attached to the patient and the navigation system reports on the alignment accuracy (Fig. 3). The surgeon uses the cutting guides to easily achieve the preoperative plan, extracting the planned donor fragment and removing the recipient's defect to assure congruency.

In the single-jaw FJTT, the donor fragment is mainly the maxilla, while the recipient retains the cranium and mandible with teeth. The donor fragment is moved to the recipient operating table following neurovascular dissection. The cutting guides are designed such that after cutting, the donor fragment is still rigidly fixed to the attached reference. This allows the surgeon to track the movement of the donor fragment with respect to the recipient with visual feedback during placement. As the surgeon places the donor fragment, the CAPE system informs the surgeon of the placement accuracy (Fig. 4) and computes real-time, hybrid cephalometrics and occlusion [20,25] (Fig. 5). Cephalometric analysis computes angles and distances between well-established human dento-skeletal landmarks, or their swine analogs [25] (Tables 1, 2; Fig. 5), to quantify facial harmony, esthetics, and occlusion [26]. The landmarks are identified preoperatively on both the donor and recipient jaw–teeth fragments and distance/angle measurements are computed automatically. Following visual confirmation, the surgeon ensures the fragment placement is appropriate and rigidly fixates the donor jaw–teeth to the recipient cranium using a standard set of titanium plates and screws.

Experiment overview

Two mock FJTT surgeries (one using swine anatomy, one using human anatomy) performed on plastic models tested the CAPE system. Each mock surgery used existing CT data (live-animal or cadaveric) as the basis for constructing the plastic models. An additional surgery was performed on a human cadaver using donor and recipient specimens obtained from the Maryland State Anatomy Board. For the swine surgery, the recipient was chosen as the smaller of the two in the setting of a large size mismatch. The donor and recipient for the human studies were arbitrarily chosen from the specimens obtained through the Maryland State Anatomy Board.

Commercial software (Mimics, Materialise, Leuven, Belgium) aided in the semi-automated segmentation and labeling of various hard tissue structures on preoperative CT data. An automatic threshold segmentation identified the bony anatomy. Manual adjustments refined the segmentation and separated the cranium and maxilla from the mandible, generating distinct surface models. Stereolithographic models made of resin (Acura ABS White, SLA 7810, 3d Systems, Rock Hill, SC, USA) were fabricated for the surgeries with high accuracy [27]. After printing, radiopaque fiducials (stainless steel beads) were implanted on the specimen in sets of (at least) four to serve as the ground truth for fragment movement. Each set of beads was placed on bony anatomy of interest (i.e., the maxilla or cranium) to facilitate postoperative registration (Fig. 6). Using small spherical beads (1.5–2.2 mm diameter) reduced metallic artifact in the subsequent CT scans and did not interfere with model segmentation or reconstruction.

Prior to each FJTT surgery, virtual planning was performed according to the CAPE protocol. The models were CT scanned at 0.45 × 0.45 × 0.6 mm resolution on a SOMATOM Definition Flash scanner (Siemens Healthcare, Germany). The scans were performed at 100 kVp, with a tube current of 421 mAs (human cadaver) or 566 mAs (plastic model). A soft tissue reconstruction kernel was used. These imaging protocols are appropriate for real patients and were shown to be effective in the human cadaver surgery. Clinically, ideal slice thickness is 1.25 mm or less. Both the anatomical structures (i.e., cranium and mandible) and the fiducials were segmented from the preoperative model, which had been created using CT data. After defining the cutting planes based on donor-to-recipient hybrid relation, patient-specific guides were designed using commercial software (FreeForm Plus, 3d Systems, Rock Hill, SC, USA; Magics, Materialise, Leuven, Belgium). The guides were printed on a Connex 500 printer (Stratasys Ltd., Eden Prairie, MN, USA) using biocompatible material (Objet Med610, Stratasys Ltd., Eden Prairie, MN, USA) (Fig. 2). The material chosen for this study allowed some structural flexibility in the guides during the swine scenario to improve positioning prior to final placement with screw fixation. Of note, this flexibility is not considered necessary in human operations but was found useful in the swine.

The surgeries followed the CAPE routine with the additional steps to analyze the donor fragment placement. Using the optical tracker, the CAPE system recorded the fixed position of the donor guide relative to the donor maxilla and the recipient guide relative to the recipient cranium. As the surgeon placed the donor fragment onto the recipient, the optical tracker acquired a "snapshot" of the unfixed relative position of the donor guide (and, by association, the donor fragment) on the recipient's cranium. The surgeon then fixated the donor fragment in place using plating fixtures (Stryker Universal Fixation System). Hot glue also helped to reinforce the final maxilla fragment position within the human mock scenario in addition to the rigid titanium plate fixation (Fig. 7).

Postoperative CT scans at 0.45 × 0.45 × 0.60 mm resolution were obtained and an automated threshold-based segmentation provided an initial labeled CT volume. Manual improvements separated the plastic models (Fig. 8). An automated, high-threshold segmentation identified the fiducials in the postoperative scan. Each fiducial was automatically identified in the CT volume as a series of connected voxels. The geometric center (average, unweighted position) of the voxels defined the center of each fiducial.

Two CT registration techniques identified the postoperative placement of the donor segment for the plastic model transplants: (1) fiducial-based registration and (2) volumetric-based registration; accuracy for the human cadaver test was measured through volumetric-based registration only. The fiducial-based registration procedure used a point-to-point registration technique [28] between the corresponding preoperative and postoperative fiducials. The volumetric-based registration employed a normalized mutual information (NMI) technique in Amira (Visualization Sciences Group, Burlington, MA, USA) to align the volumes. To ensure the best accuracy, the raw preoperative and postoperative CT data were masked with the volume labels to only compare analogous bony anatomy (e.g., the recipient cranium). Manual alignment initialized the NMI registration routine.

Three types of errors were measured in this study: (1) intraoperative to planned; (2) postoperative to planned; and (3) intraoperative to postoperative (navigation error). The intraoperative placement is measured through CT data, and the postoperative placement is measured as described above. The measured transformations were applied to the preoperative surface model of the maxilla to maintain a consistent model and coordinate frame for comparison. The distance error between corresponding vertices on the maxilla surface model was computed—there were 4,975 vertices in the swine plastic model, 4,939 in the human plastic model, and 7,412 in the human cadaver.

Results

Due to significant (unpublished) practice with the CAPE system, we completed each mock surgery without complication. Moreover, the nature of the mock surgeries (no soft tissue, no bodily fluids, etc.) enabled improved access to the dento-skeletal anatomy of interest. During the procedures, we identified a few areas of improvement, including:

1. In the human scenario, attaching the donor fragment to the recipient is not as simple as in the swine operation. With swine, there is a single curve (cutting plane) along the bone, while for the human case, cuts are made in three separate plane

locations (Fig. 9). The human approach, then, requires multiple fixation points along multiple planes. Several potential improvements exist for this problem, including an updated guide design, which “locks” the fragment in place by temporarily fixing the donor guide and recipient guide together.

2. The reference attachment originally designed for the swine’s skull is not appropriate for the human skull. Specifically, the curvature of the human skull did not allow for full fixation of the reference hardware as planned. However, a new redesigned version functions on both swine and human, has a low profile and light-weight design, and will not disrupt the surgeon (Fig. 10).

The intraoperative model-to-patient registration routine for the CAPE system exhibited errors of 0.727 and 0.306 mm for the human plastic model donor and recipient, respectively. The errors on the human plastic models were comparable to those exhibited on swine—0.510 and 0.357 mm for swine donor and recipient, respectively. Human cadaveric testing showed registration errors of 1.22 and 0.745 mm for the donor and recipient, respectively.

The different postoperative registration techniques (fiducial-based and volumetric-based) showed similar error values (Table 3). As such, the volumetric-based registration errors are used for the remainder of the paper to enable comparison between tests with the plastic models and the human cadaver. Error analysis on the intraoperative placement of the donor fragment indicated reduced error on the swine compared with the human. The average navigation error (postoperative measurement compared to intraoperative measurement) for both plastic model tests did not exceed 1.250 mm regardless of postoperative registration technique (Table 3). There was increased error in the final placement of the donor fragment with respect to the planned position for the human plastic model test case (2.91 mm) compared to the swine test case (2.25 mm); however, intraoperative accuracy between the plastic model tests was comparable. Human cadaver testing demonstrated increased navigation error (3.59 mm) compared to the plastic models, but the final placement error was 2.26 mm—lower than the human plastic model.

Each of the plastic model surgeries had the mandible (lower jaw) disconnected from the cranium. This makes postoperative occlusal evaluation difficult. However, results from the cadaver testing showed the postoperative hybrid occlusion matched the planned occlusion. The plan aligned the arches to provide a “reasonable occlusion” for this hybrid jaw in relation to arch alignment, occlusal plane, and tooth interdigitation, as estimated by the surgeon and periodontist. An open bite was planned on the posterior right, with posterior left contact, centered alignment of the central incisors, and minimal overbite/overjet (postoperatively measured to be less than 4 mm). The planned occlusion kept acceptable cephalometric measures with a sella–nasion–A point (SNA) angle of 81 degrees indicative of a normal maxillary-cranial relationship [29]. As noted by the fragment accuracy, the cuts were achieved and the postoperative results were qualitatively near the planned occlusion.

Discussion

The CAPE system was developed to improve outcomes in complex craniomaxillofacial procedures including Le Fort-based FJTT [19,20]. This paper presents a feasibility study of the navigation system by comparing measured intraoperative data with postoperative data. Moreover, this study reports on the accuracy with which we achieved a planned alignment of the donor face–jaw–teeth fragment onto the recipient utilizing a size-mismatched scenario in both swine and humans. This exhibited the capability of transitioning the CAPE system from swine (the basis of the initial development) to human anatomy without making changes to the system.

The results from this study exhibit the feasibility of intraoperative, navigated guide placement and real-time, fragment tracking. While results on the swine model reported higher (postoperative) positioning accuracy relative to the plan (2.25 mm as compared to 2.91 for the human plastic model), the accuracy relating the postoperative position and intraoperative position were comparable (1.21 mm as compared to 0.85 mm for the human model). The reported accuracy on the human model with no system changes bodes well for future applications of this system to FJTT and various procedures within craniofacial orthognathic surgery. Moreover, the final position of the donor maxilla fragment could not be measured since the guide must be detached before full fixation—this likely indicates improved overall accuracy from what this paper reports.

Cadaveric testing showed increased navigation error as compared to the plastic model surgeries. The main contributor to this is the increase in error of the donor and recipient registrations, an average of 0.98 mm for the cadaver test versus 0.48 mm for the plastic models. This is expected given the complexity of the cadaveric environment—soft tissue restrictions like rigor mortis, minimal bony exposure—as compared to plastic models. However, guide performance in the cadaveric environment (measured by the postoperative positioning error) was on par with the swine plastic model, and better than the human plastic model. While the advantage of navigating the guide placement cannot be established with this work, one can consider scenarios in which, because of the existence of the residuals of soft tissue over the bone surface, the navigated guide may end up improving the placement accuracy. More importantly, the trackable guide is notably useful as a dynamic reference for measuring real-time cephalometrics and allowing visual feedback during donor fragment placement onto the recipient

Compared to navigation systems for other surgeries (e.g., orthopedics), this system presents significant challenges. Orthopedic surgery has an advantage of large or (comparatively) thick bones used to fix reference devices. For this surgery, one is limited to the thickness of the skull; penetration of screws into the brain of either the donor or recipient would be a significant problem. As such, much smaller (about 4 mm threaded length and 2 mm diameter) screws fix the reference device on the parietal skull compared to at least 20 mm threaded length and 3 mm diameter screws used in optically navigated orthopedic surgery (e.g., Ortho Navigation, Medtronic, Minneapolis, MN, USA; Brainlab Image-Guide Surgery Systems, Munich, Germany; [30,31]). However, the reported registration accuracy matches that reported for surface-based registration in orthopedic surgery [31].

Some difficulties transitioning from swine surgery to human surgery were noted during the mock surgeries. One significant obstacle was the plate-screw fixation process of the donor fragment onto the recipient. One potential fix is an improved guide design that incorporates a locking mechanism for attaching the donor and recipient guides. This would allow the surgeon to partially fix the fragment using guides in the desired location, check the accuracy of the placement using the system, and fully fixate the fragment using rigid titanium plates. In addition, the initial reference designed for the swine skull did not translate well to human anatomy. The improved, lower-profile design of the new reference geometry further enables this translational research and updates the system for both types of environments (human and swine).

The integration of cutting guides and navigation potentially allows the CAPE system to achieve higher accuracy than either system independently. Recent literature [32] on a CAD/CAM system using non-navigated cutting guides report 7.18 mm error in predicted compared with actual placement of a Le Fort III-based maxilla and mandible transplantation. The results reported in this study comparing postoperative location to the plan (2.96 mm translational error for a Le Fort-based, single-jaw–teeth transplant for human) suggest significant improvement from a non-navigated cutting guide positioning and fragment transplant—and may therefore represent a major advancement in computer-assisted technologies applicable to orthognathic surgery. The cutting guides help the surgeon perform cuts at pre-defined locations and angles, which may not be achievable with as much accuracy using navigation alone.

The navigation system helps ensure that the cutting guides are placed appropriately, avoiding numerous sources of “surgeon-related” and “manufacturing-related” error. Previous research identified the potential for cutting guides to be positioned and secured with some small error; the navigation component can help the surgeon identify when that error occurs and correct the guide positioning [20]. Although the use of plastic models is a limitation for this study, the mock environment reduces many potential error sources and cofounding variables such as bleeding bone and inconsistent soft tissue contraction/relaxation. The accessibility of the entire plastic model allows the surgeon to digitize registration points at many locations; this may conflict with the reduced bony exposure in a clinical environment. However, these plastic models did allow the necessary position flexibility to assess the CAPE system accuracy (at various time points throughout the surgery) via frequent model manipulation—which would not be feasible in the cadaver or live surgery setting.

The materials used for the bone models in the plastic models were significantly more difficult to interact with as compared to real bone. For instance, the surgeon reported increased difficulty in attaching the guides and fixation plates since the self-drilling bone screws were less effective as compared to real bone. Additionally, the material used for printing the cutting guides had some mechanical flexibility. This flexibility is useful for accounting for minor differences in the CT segmentation and actual anatomy during surgery. However, the navigation system models this as a rigid guide and cannot accurately capture these small deviations.

The described technology in this work relies on the use of diagnostic CT information for preoperative planning. Cone-beam CT is an emerging technology in various applications including dental and head/neck surgery, which which also offers high resolution images.

This increased resolution offers more information about the bone, but the poor contrast and high noise may be detrimental and will increase segmentation/ planning time. Most cone-beam CTs of the head/neck require the patient to be seated upright—a challenging task to achieve with the donor.

Transitioning this system to clinical trials still requires a significant amount of testing. The human cadaver test showed that the presence of soft tissue in the CT scan does not hamper the segmentation, model reconstruction, or cutting guide design, but will impact the registration. Moreover, the cutting guide can be affixed with only the skin incisions required for the transplant. Some clinical donors or recipients may present with metallic fillings in teeth causing artifact in the CT volume. These artifacts will pose difficulty in truly predicting the hybrid occlusion resulting from the single-jaw–teeth transplant and will need to be addressed in future iterations on this work.

Planning routines for each surgery can likely be completed within 5 h per case. This includes segmentation, alignment of the donor CT to recipient, planning the cutting planes, and designing the patient-specific guides. The guides must be printed overnight, but this is a “set and forget” operation. While this may add additional time preoperatively, it can likely save time during the operation and lead to improved outcomes—a very appropriate tradeoff.

The tools and techniques developed with this system may provide a substantial benefit to more traditional orthognathic surgery, ENT surgery, neurosurgery, and head/neck surgery. For example, the features within the CAPE system—such as real-time cephalometry—may reduce or remove the time-intensive process of hand-molded acrylic splints or costly process of virtual occlusal splint fabrication for all orthognathic cases. The stable reference mounted on the parietal bone provides a rigid navigation frame that may allow surgeons to do away with conventional pinning techniques used to maintain skull rigidity (i.e., skull clamp), especially in instances where concomitant scalp reconstruction is required.

In conclusion, this study presents the feasibility and translation of the CAPE system for Le Fort-based face–jaw–teeth transplantation. This preliminary data suggest promising results further showing the feasibility of the system and showing full translational capabilities to human anatomy. Future work will focus on validation through human cadaver studies, and moving forward with live swine surgery for additional feature development and pre-clinical safety testing. The CAPE system offers surgeons a new path forward in achieving improved outcomes in craniomaxillofacial surgery including Le Fort-based, maxillofacial transplantation. Furthermore, these technological advancements may be carried over into other surgical areas including orthognathic surgery, ENT surgery, neurosurgery, and head/neck surgery.

Acknowledgments

The authors gratefully thank Dr. Kevin Wolfe for his expertise and design of the new reference fixation on the human skull. Funding was provided by the 2011 Basic Science Research grant from American Society of Maxillofacial Surgeons, 2012–2014 Academic Scholar Award from American Association of Plastic Surgeons, the Accelerated Translational Incubator Program Award at Johns Hopkins University’s Institute for Clinical and Translational Research (funded by National Institutes of Health), Independent Research and Development funds from the Johns Hopkins Applied Physics Laboratory, and the Abell Foundation Award/Johns Hopkins Alliance for Science and Technology development. This study was made possible, in part, by the Johns Hopkins Institute for

Clinical and Translational Research (ICTR) which is funded in part by the National Center for Advancing Translational Sciences (NCATS), a component of the National Institutes of Health (NIH), and NIH Roadmap for Medical Research. Its contents are solely the responsibility of the authors and do not necessarily represent the official view of the Johns Hopkins ICTR, NCATS or NIH (NCATS Grant # UL1TR000424-06).

References

1. Gordon CR, Susarla SM, Peacock ZS, Cetrulo CL, Zins JE, Papay F, Kaban LB. Osteocutaneous maxillofacial allotransplantation: lessons learned from a novel cadaver study applying orthognathic principles and practice. Plast Reconstr Surg. 2011; 128(5):465e–479e.
2. Siemionow M, Ozturk C. An update on facial transplantation cases performed between 2005 and 2010. Plast Reconstr Surg. 2010; 128(6):707e–720e.
3. Gordon CR, Susarla SM, Peacock ZS, Kaban LB, Yaremchuk MJ. Le Fort-based maxillofacial transplantation: current state of the art and a refined technique using orthognathic applications. J Craniofac Surg. 2012; 23(1):81–87. [PubMed: 22337380]
4. Mohan R, Borsuk DE, Dorafshar AH, Wang HD, Bojovic B, Christy MR, Rodriguez ED. Aesthetic and functional facial transplantation: a classification system and treatment algorithm. Plast Reconstr Surg. 2014; 133(2):386–397. [PubMed: 24469171]
5. Siemionow MZ, Papay F, Djohan R, Bernard S, Gordon CR, Alam D, Hendrickson M, Lohman R, Eghtesad B, Fung J. First us near-total human face transplantation: a paradigm shift for massive complex injuries. Plast Reconstr Surg. 2010; 125(1):111–122. [PubMed: 19770815]
6. Meningaud J-P, Hivelin M, Benjoar M-D, Toure G, Hermeziu O, Lantieri L. The procurement of allotransplants for ballistic trauma: a preclinical study and a report of two clinical cases. Plast Reconstr Surg. 2011; 127(5):1892–1900. [PubMed: 21228738]
7. Gordon CR, Siemionow M, Papay F, Pryor L, Gatherwright J, Kodish E, Paradis C, Coffman K, Mathes D, Schneeberger S, et al. The world's experience with facial transplantation: what have we learned thus far? Ann Plast Surg. 2009; 63(5):572–578. [PubMed: 19806039]
8. Dorafshar AH, Bojovic B, Christy MR, Borsuk DE, Iliff NT, Brown EN, Shaffer CK, Kelley TN, Kukuruga DL, Barth RN, et al. Total face, double jaw, and tongue transplantation: an evolutionary concept. Plast Reconstr Surg. 2013; 131(2):241–251. [PubMed: 23076416]
9. Taylor, RH. Computer integrated surgery: technology and clinical applications. Cambridge: The MIT press; 1996.
10. Taylor, R.; Joskowicz, L. Standard handbook of biomedical engineering and design. 2nd edn.. New York: McGraw Hill; 2003. Computer-integrated surgery and medical robotics; p. 29-33.
11. Bell RB. Computer planning and intraoperative navigation in cranio-maxillofacial surgery. Oral Maxillofac Surg Clin N Am. 2010; 22(1):135–156.
12. Bookstein FL, Grayson B, Fellingham L, McCarthy JG, 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(6):877–885. [PubMed: 3714886]
13. Altobelli DE, Kikinis R, Mulliken JB, Cline H, Lorensen W, Jolesz F, et al. Computer-assisted three-dimensional planning in craniofacial surgery. Plast Reconstr Surg. 1993; 92(4):576–585. [PubMed: 8356120]
14. Hirsch DL, Garfein ES, Christensen AM, Weimer KA, Saddeh PB, Levine JP. Use of computer-aided design and computer-aided manufacturing to produce orthognathically ideal surgical outcomes: a paradigm shift in head and neck reconstruction. J Oral Maxillofac Surg. 2009; 67(10): 2115–2122. [PubMed: 19761905]
15. Rudman K, Hoekzema C, Rhee J. Computer-assisted innovations in craniofacial surgery. Faci Plast Surg. 2011; 27(04):358–365.
16. Sabol JV, Grant GT, Liacouras P, Rouse S. Digital image capture and rapid prototyping of the maxillofacial defect. J Prosthodont. 2011; 20(4):310–314. [PubMed: 21438958]
17. Liacouras P, Garnes J, Roman N, Petrich A, Grant GT. Designing and manufacturing an auricular prosthesis using computed tomography, 3-dimensional photographic imaging, and additive manufacturing: A clinical report. J Prosthet Dent. 2011; 105(2):78–82. [PubMed: 21262404]

18. van Noort R. The future of dental devices is digital. Dent Mater. 2012; 28(1):3–12. [PubMed: 22119539]
19. Gordon CR, Swanson EW, Susarla SM, Coon D, Rada E, Al Rakan M, Shores JT, Bonawitz SC, Fishman EK, et al. Overcoming cross-gender differences and challenges in Le Fort-based, craniomaxillofacial transplantation with enhanced computer-assisted technology. Ann Plast Surg. 2013; 71(4):421–428. [PubMed: 24025655]
20. Gordon CR, Murphy RJ, Coon D, Basafa E, Otake Y, Al Rakan M, Susarla S, Swanson E, Fishman E, et al. Preliminary development of a workstation for craniomaxillofacial surgical procedures: introducing a computer-assisted planning and execution system. J Craniofac Surg. 2014; 25(1):273–283. [PubMed: 24406592]
21. Basafa E, Murphy RJ, Gordon CR, Armand M. Modeling the biomechanics of swine mastication—an inverse dynamics approach. J Biomech. 2014; 47(11):2626–2632. [PubMed: 24957923]
22. Bojovic B, Dorafshar AH, Brown EN, Christy MR, Borsuk DE, Hui-Chou HG, Shaffer CK, Kelley TN, Sauerborn PJ, Kennedy K, Hyder M, Brazio PS, Philosophe B, Barth RN, Scalea TM, Bartlett SD, Rodriguez ED. Total face, double jaw, and tongue transplant research procurement: an educational model. Plast Reconstr Surg. 2012; 130(4):824–834. [PubMed: 22691842]
23. Al Rakan M, Shores JT, Bonawitz S, Santiago G, Christensen J, Grant G, Murphy RJ, Basafa E, Armand M, Otovic P, et al. Ancillary procedures necessary for translational research in experimental craniomaxillofacial surgery. J Craniofac Surg. 2014 (in Press).
24. Besl PJ, McKay ND. A method for registration of 3-d shapes. IEEE Trans Pattern Anal Mach Intell. 1992; 14(2):239–256.
25. Santiago GF, Susarla SM, Rakan MA, Coon D, Rada EM, Sarhane K, et al. Establishing cephalometric landmarks for the translational study of Le Fort-based facial transplantation in swine: Enhanced applicaitons using computer-assisted surgery and custom cutting guides. Plast Reconstr Surg. 2014; 135(5):1138–1151. [PubMed: 24445879]
26. Zins, JZ.; Gordon, CR. Craniofacial applications in facial aesthetic surgery. In: Zins, JZ.; Gordon, CR., editors. Handbook of Craniomaxillofacial Surgery. Singapore: World Scientific Publishing; 2014.
27. Taft RM, Kondor S, Grant GT. Accuracy of rapid prototype models for head and neck reconstruction. J Prosthet Dent. 2011; 106(6):399–408. [PubMed: 22133397]
28. Horn BKP. Closed-form solution of absolute orientation using unit quaternions. J Opt Soc Am A. 1987; 4(4):629–642.
29. Connor AM, Moshiri F. Orthognathic surgery norms for American black patients. Am J Orthod. 1985; 87(2):119–134. [PubMed: 3855605]
30. Lepistö J, Armand M, Armiger RS. Periacetabular osteotomy in adult hip dysplasia—developing a computer aided real-time biomechanical guiding system (BGS). Suom Ortop Traumatol. 2008; 31(2):186–190.
31. Sugano N, Sasama T, Sato Y, Nakajima Y, Nishii T, Yonenobu K, Tamura S, Ochi T. Accuracy evaluation of surface-based registration methods in a computer navigation system for hip surgery performed through a posterolateral approach. Comput Aided Surg. 2001; 6(4):195–203. [PubMed: 11835614]
32. Dorafshar AH, Brazio PS, Mundinger GS, Mohan R, Brown EN, Rodriguez ED. Found in space: computer-assisted orthognathic alignment of a total face allograft in six degrees of freedom. J Oral Maxillofac Surg. 2014; 72(9):1788–1800. [PubMed: 24656428]

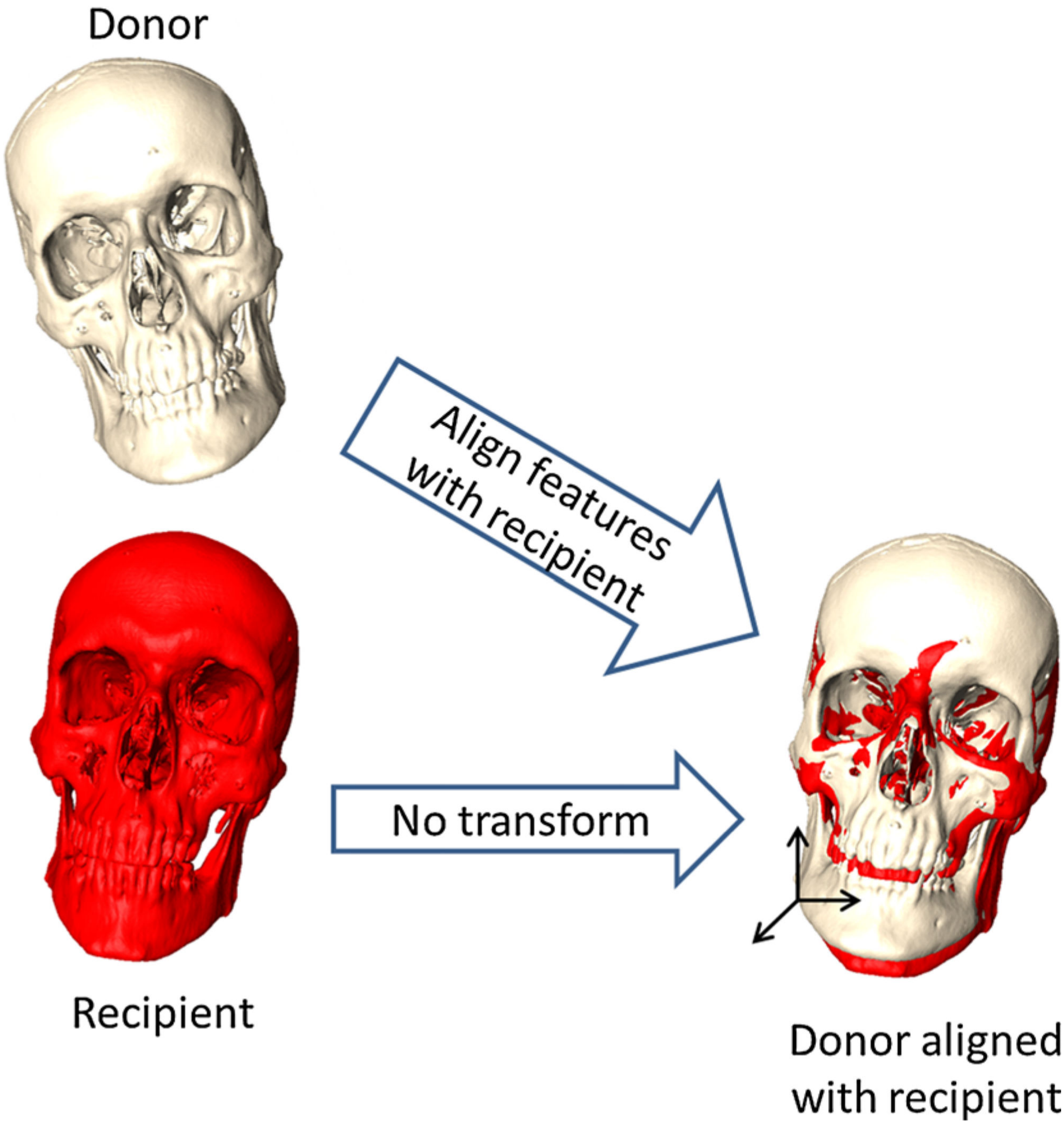

Fig. 1.
Alignment of the donor and recipient surface models. The combined surface model has a common coordinate frame between the donor and recipient

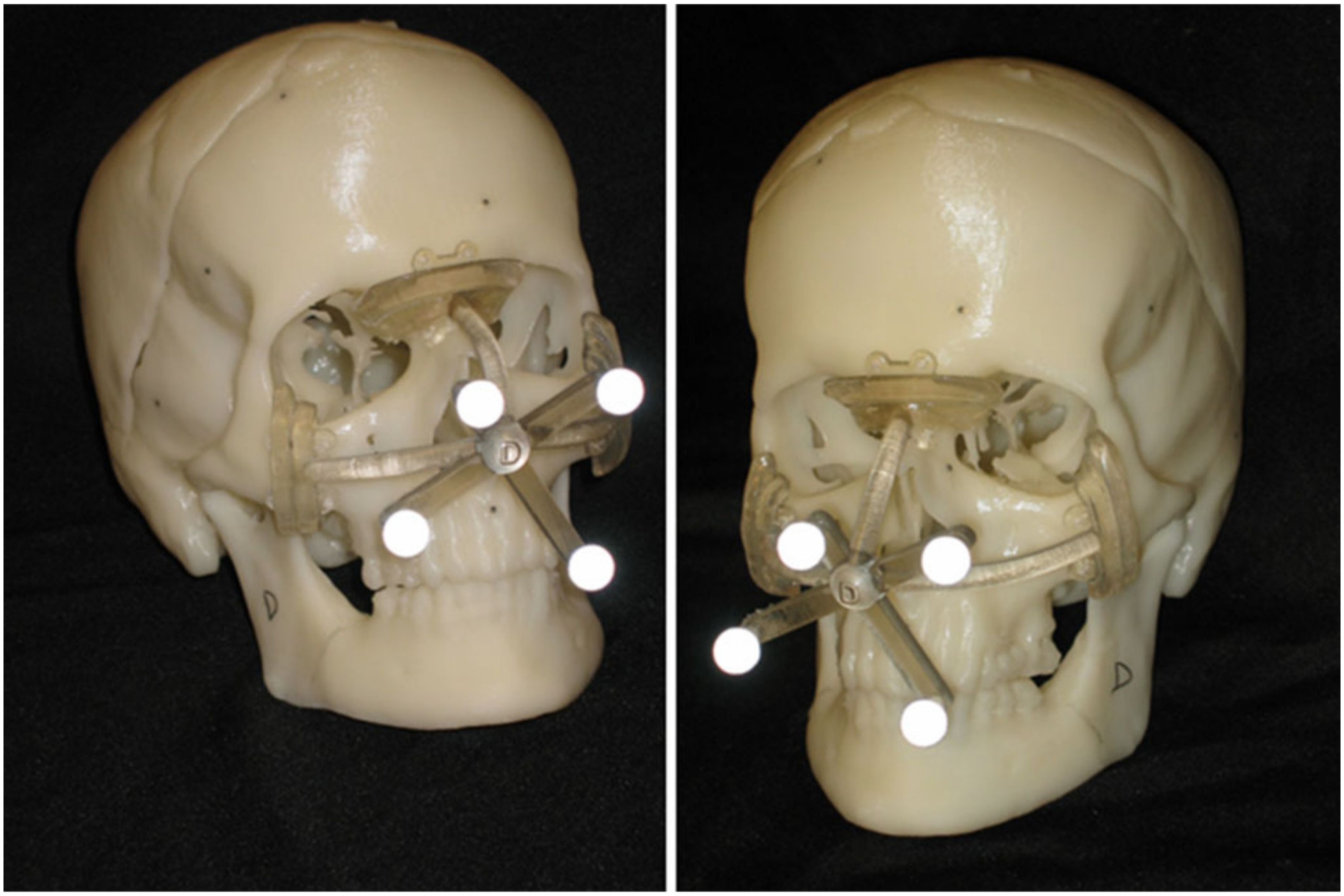

Fig. 2.
Patient-specific cutting guides on donor specimen with an attached reference geometry. The reference geometry is tracked through the environment by the four spheres, which reflect infrared light

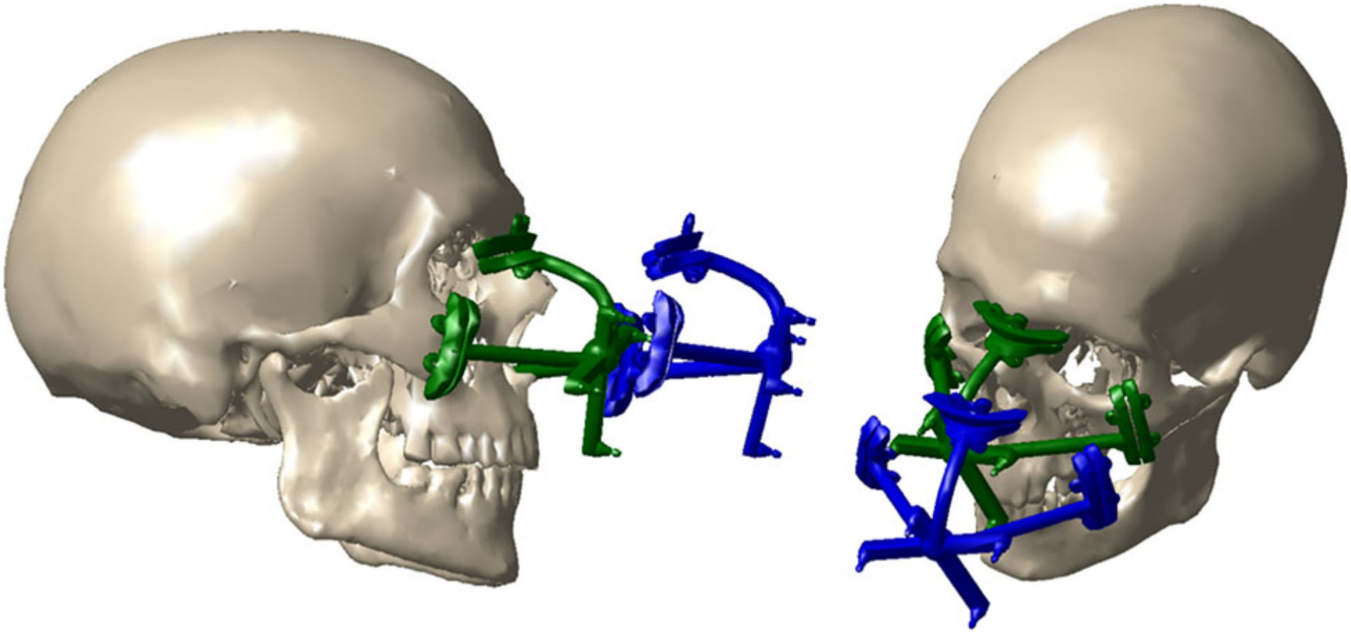

Fig. 3.

The patient model display of the CAPE system with the planned position of the guide (*green*) and the actual position of the guide (*blue*) during guide placement

Fig. 4.
The CAPE system visualizes the donor fragment as it is placed onto the recipient

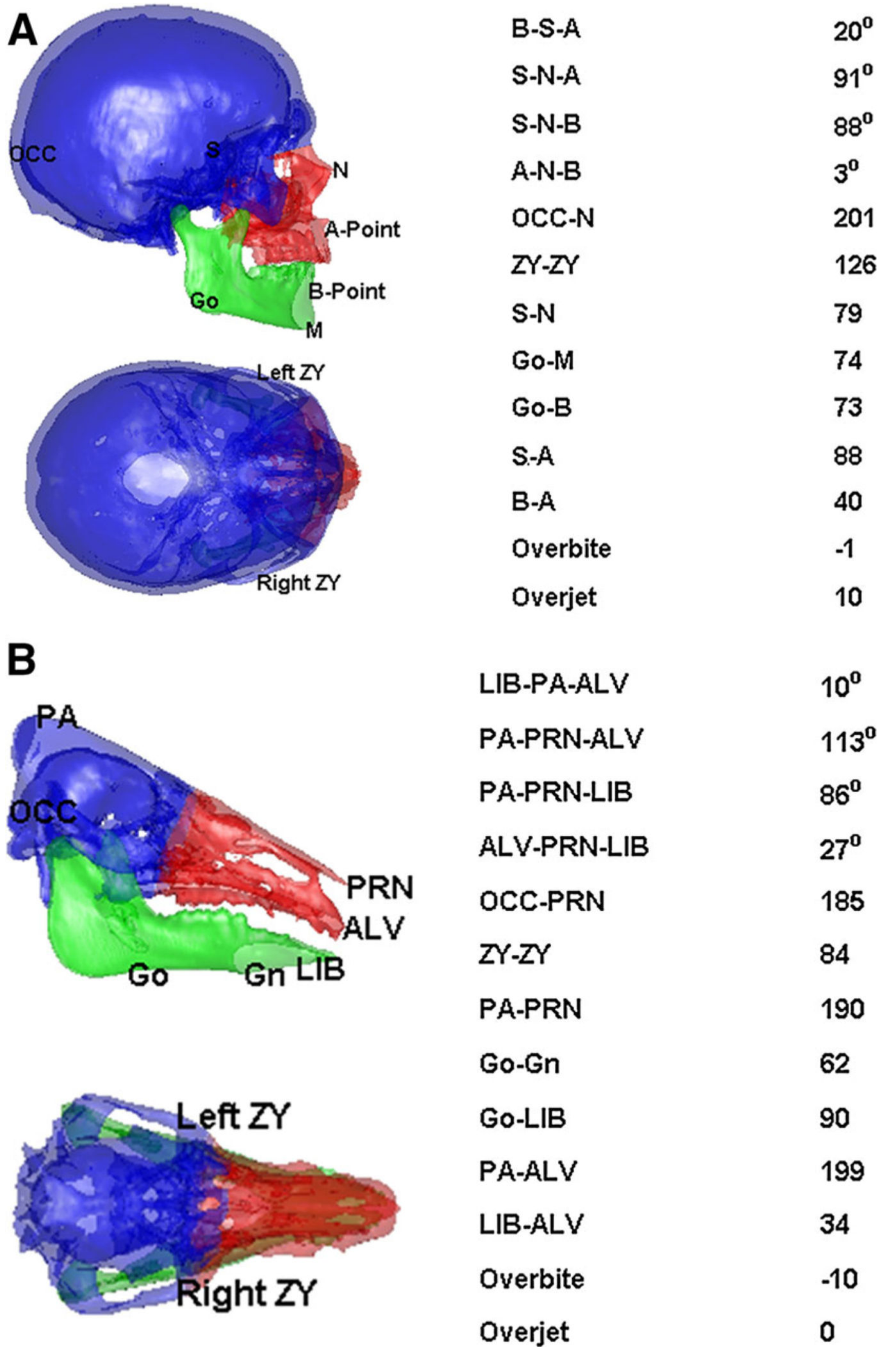

Fig. 5.

Example real-time cephalometric display provided by the CAPE system to the surgeon for both human (**a**) and swine (**b**). This display is updated as the donor jaw fragment is moved with respect to the recipient cranium, and the cephalometric parameters are reported to the surgeon. Distances between points are measured in mm and angles are measured in degrees

Fig. 6.
Printed plastic human skull (recipient) with fiducials attached and simulated trauma

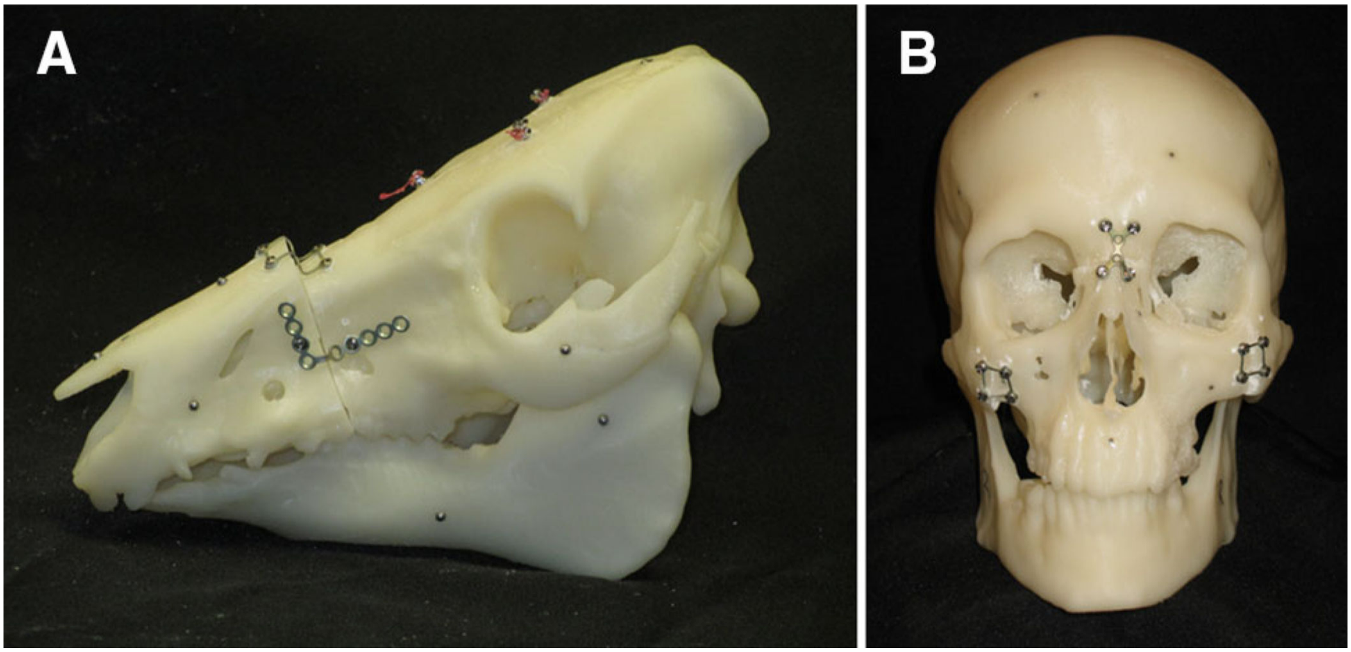

Fig. 7.

Final placement of donor jaw–teeth segment onto the recipient's cranium/mandible for (**a**) swine and (**b**) human

Author Manuscript
Author Manuscript
Author Manuscript

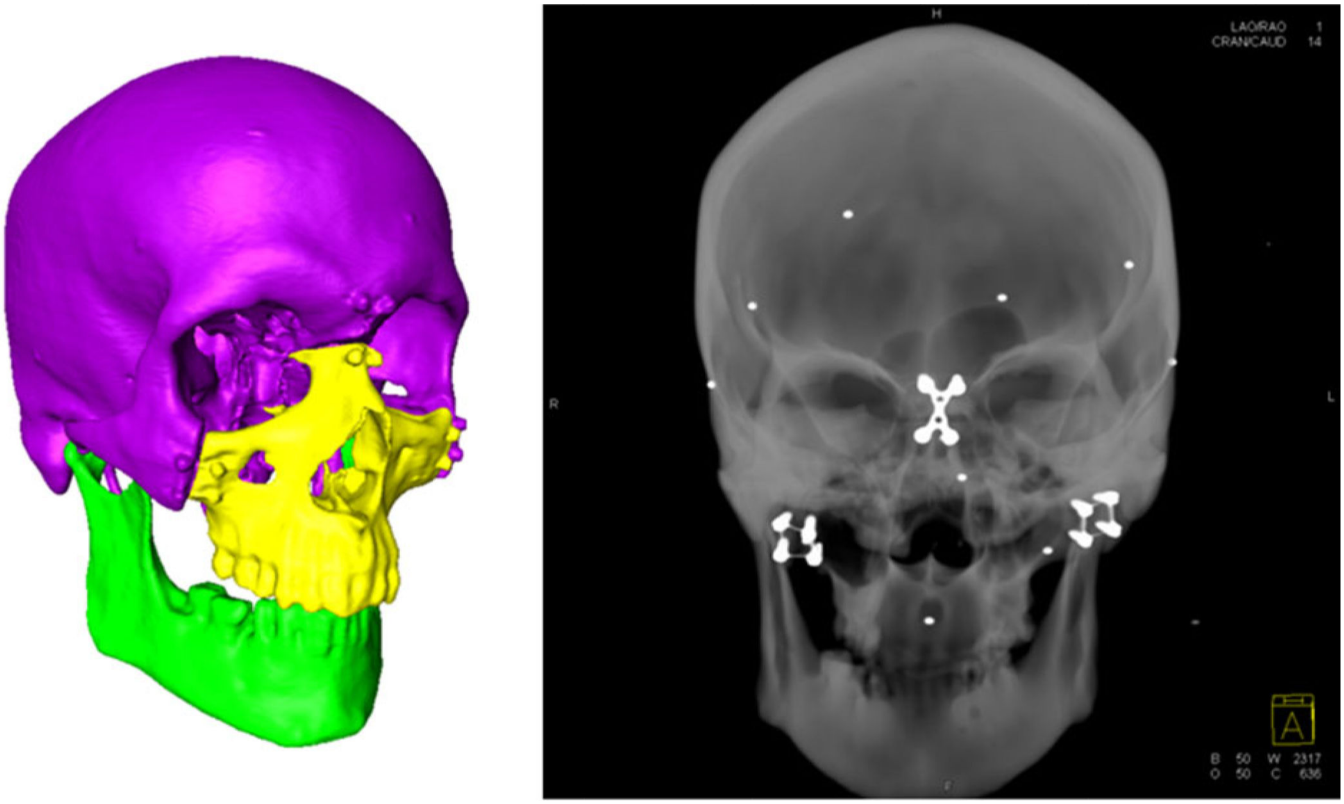

Fig. 8.

Postoperative CT segmentation of the human plastic models (*left*) and reconstructed projection view with fiducials highlighted (*right*)

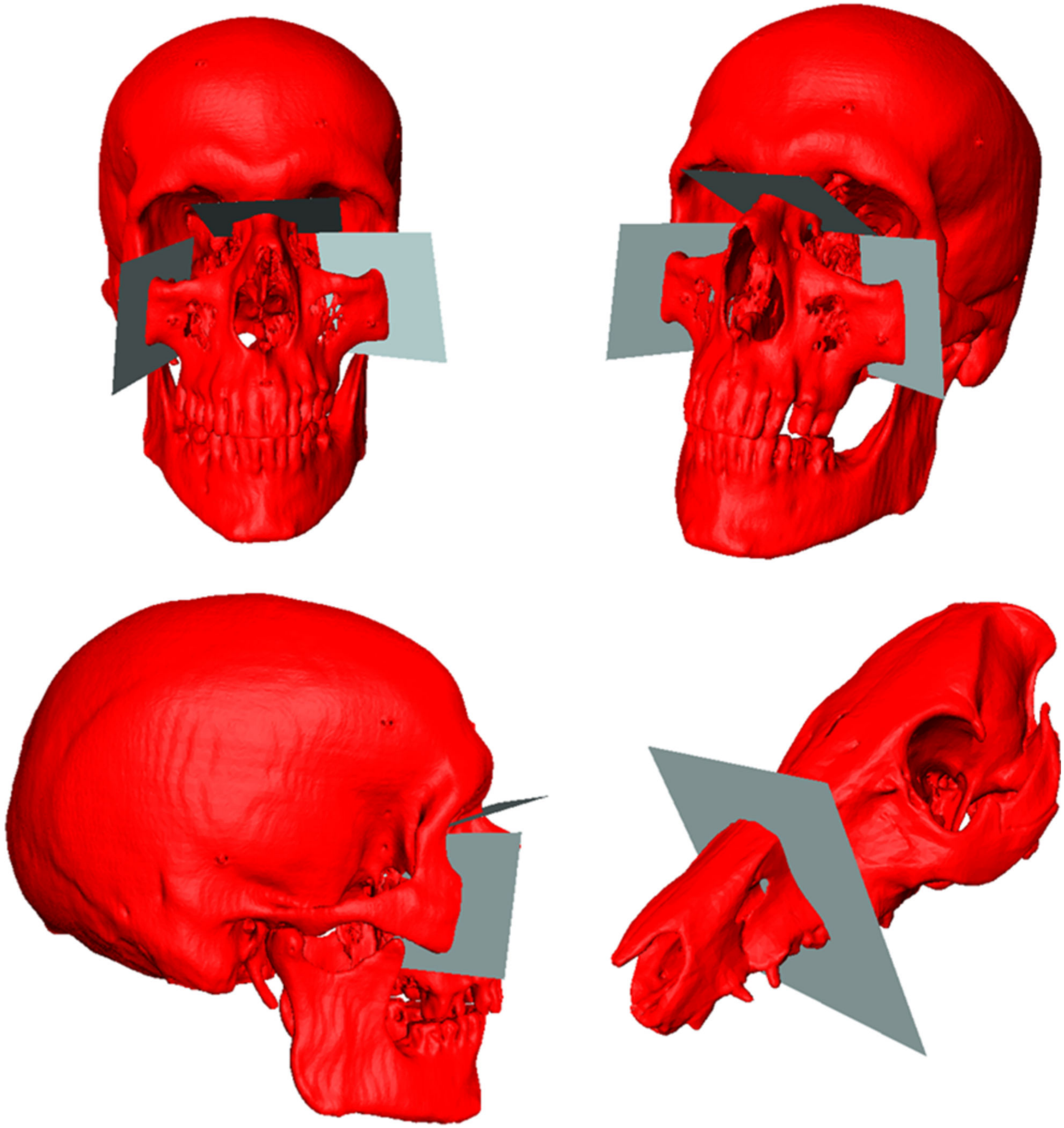

Fig. 9.
The cut planes on the swine and human models

Author Manuscript
Author Manuscript
Author Manuscript

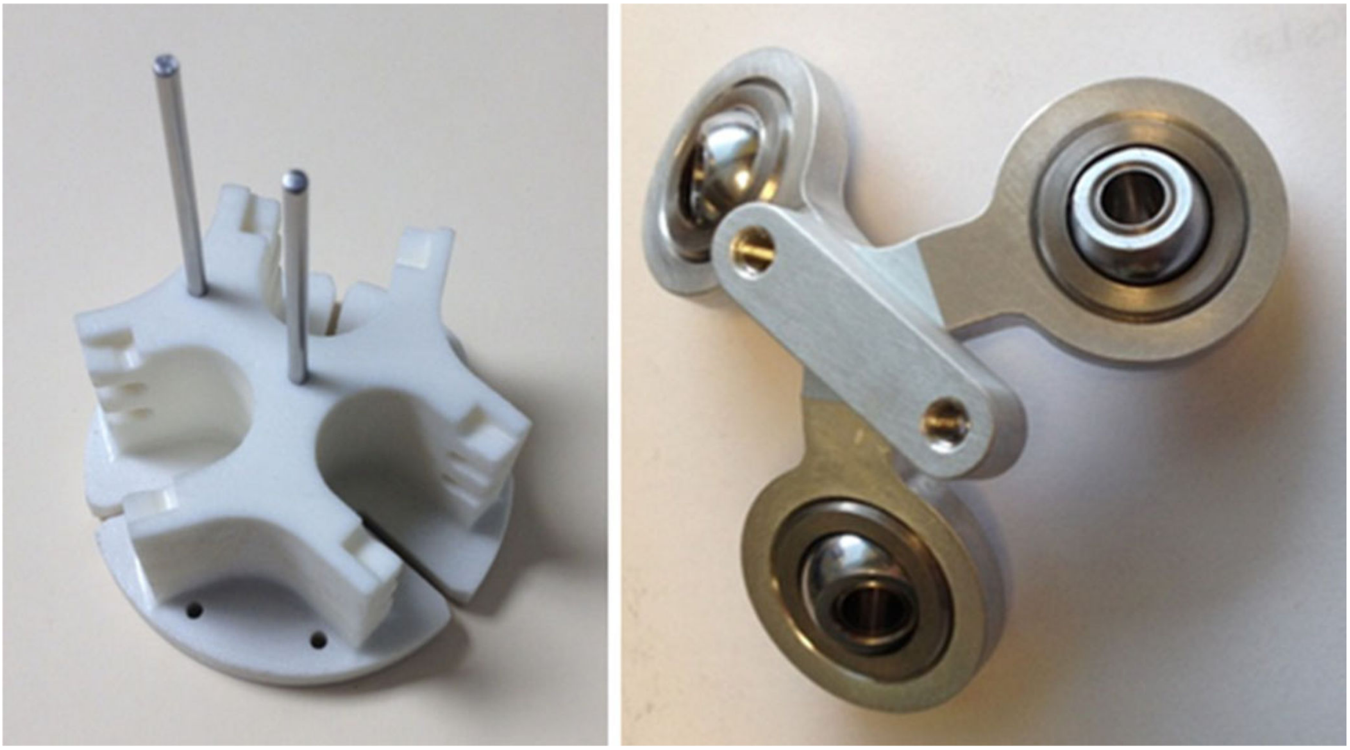

Fig. 10.
Cranial reference attachment designed for swine (*left*) and redesigned version for human and swine anatomy (*right*)

Table 1

Human and swine cephalometric landmarks [25]

Human landmark	Swine landmark
Gonion (Go)	Gonion (Go)
Nasion (N)	Pronasale (PRN)
A point (A)	Alveolare (ALV)
B point (B)	Lower Incisor Base (LIB)
Sella (S)	Parietale (Pa)
Menton (M)	Gnathion (Gn)
Left/right Zygoma (ZY)	Zygion (Zy)
Os occipitale (OCC)	Os occipitale (OCC)

Author Manuscript

Author Manuscript

Author Manuscript

Table 2

Definition of the cephalometric measurements

Measurement	Definition
B–S–A	Angle between the B point, sella, and A point
S–N–A	Angle between the sella, nasion, and A point
S–N–B	Angle between the sell, nasion, and B point
A–N–B	Angle between the A point, nasion, and B point
Occ–N	Distance between the os occipitale and the nasion
Zy–Zy	Distance between the left and right zygomas
S–N	Distance between the sella and the nasion
Go–M	Distance between the gonion and the menton
Go–B	Distance between the gonion and the B point
S–A	Distance between the A point and the sella
B–A	Distance between the A point and the B point
Overbite	Vertical overlap between upper and lower teeth
Overjet	Horizontal overlap between upper and lower teeth

Table 3

Placement error for human and swine surgeries

	Intraop to planned	Registration type	Postop to planned	Postop to intraop
Human [plastic model]	2.62 ± 0.36	Fiducial	2.96 ± 0.53	1.23 ± 0.35
		Volume	2.91 ± 0.42	0.85 ± 0.28
Swine	2.68 ± 1.10	Fiducial	1.81 ± 0.77	1.20 ± 0.28
		Volume	2.25 ± 0.97	1.21 ± 0.32
Human [cadaver surgery]	3.29 ± 0.87	Volume	2.26 ± 0.18	3.59 ± 1.78

Errors are in mm, presented as mean ± SD