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Review Article

Application of computer-assisted surgery techniques in the management of zygomatic complex fractures

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ABSTRACT

Patients suffering from zygomatic complex fractures always present facial deformity and dysfunctions, and thereafter develop psychological and physiological problems. It is really hard to get an ideal prognosis for the zygomatic complex fractures because of the complicated anatomical structures. Computer-assisted surgery techniques, as the new emerging auxiliary methods, can optimize the surgical protocol, predict operation outcomes, and improve the accuracy and quality of the operation. Meanwhile the postoperative complications can be reduced effectively. This review aims to provide a comprehensive overview of the application of computer-assisted surgery techniques in the management of zygomatic complex fractures.

The zygomatic bone articulates with the frontal, sphenoid, temporal, and maxillary bones, composing the zygomatic complex with those adjacent structures. The zygomatic complex strongly contributes to midfacial width and protrusion, thus playing a vital role in facial contour,[1,2] rendering it vulnerable to injuries quite commonly in the midface region.[2–4] Among facial fractures, zygomaticomaxillary complex fracture is one of the most frequent.[1,2,4] The zygomatic complex fractures are grabbing increasingly extensive attention because they can cause morphologic disfigurement and functional impairment, including ocular motility restriction, facial asymmetry, and so forth, which in turn may lead to serious mental disorders and social dysfunction for patients, especially comminuted fractures and delayed fractures. Therefore, from the perspective of both aesthetic and functional, it is mandatory that zygomatic complex fractures be properly diagnosed and adequately managed.[5]

Therapies for fractures in the area of zygomatic complex include conservative treatment and surgery. The most common indication for conservative treatment is non-dislocated zygomatic bone fractures without functional disorders;[6] while surgery is necessary in the dislocated, instable, and comminuted zygomatic complex fractures.[6,7] Open reduction with internal fixation (ORIF) should be considered as the main and reliable option for restoring appearance. The key of the surgery is to restore and maintain pre-injury facial skeletal configuration.[8] However, as subjected to the vague edges of the fractures and limited surgical field, performance of the surgery largely depends on the clinical experiences and skills of the surgeons. Frequently, patients still appear different degrees of postoperative complications, like facial asymmetry, enophthalmos, and so forth, especially in cases of severe comminuted fractures and delayed fractures. These unsatisfactory outcomes are usually caused by improper operation protocol, over- or under-reductions, and inadequate fixation. Therefore, the management of zygomatic complex fractures is still a challenge to the surgeons.[9,10]

The development of computer technology has innovated several computer-assisted surgical (CAS) techniques for the diagnosis, virtual surgical planning (VSP) and treatment in the field of maxillofacial fractures.[11–14] These techniques, including VSP, rapid prototyping 3D models, surgical navigation, individual surgical templates & preshaped implants, and robotic or telepresence surgeries, have been applied in the management of zygomatic complex fractures for recent years. This review aims to provide a comprehensive overview of the application of computer-assisted surgery techniques in the management of zygomatic complex fractures.

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VSP

VSP is grounded on a variety of medical image data and virtual reality technology to reconstruct a virtual model, and permits surgeons to simulate the operation on the virtual model. Coupled with a method of transferring the plan to the patient, VSP enables the surgeon to make an accurate diagnosis, provides a predictable means of 3D reconstruction, and facilitates the analysis of postoperative changes.[15–17] Moreover, displacement direction and distance of segments can be measured. Then, based on these measured preoperative data, the surgeons could move the segments accordingly. Several kinds of related VSP software are currently available, such as MIMICS, iPlan CMF, Voxim, Medtronic Treon system, and so on.[18] iPlan CMF is simple and easy to grasp. MIMICS is a powerful software that permits surgeons to perform various operations to build models in demand.[19,20] So, iPlan CMF and MIMICS are clinically used mostly.

The processes of VSP are as follows: (1) 2D data collection, including CT, cone-beam CT or MRI; (2) input of Scanned Digital Imaging and Communications in Medicine (DICOM) images to related software for 3D modeling for purposes of visualization, diagnosis, and performance; (3) virtual segmentation and virtual reductions with or without mirror imaging technique; (4) establishment of a planning model, template or implant.[18,21]

The applications of VSP in the management of zygomatic complex fractures can be summarized as: (1) to assist acquiring exact and comprehensive diagnosis; (2) to provide surgical planning and preoperative simulation; (3) to provide data for the design of reposition templates or personalized preshaped implants[22,23]; (4) to predict operation outcomes, evaluate the feasibility of operation; and (5) to serve as a communication tool between surgeon and patient.[17] In a series of 59 patients with orbital and midface fractures, Hohlweg-Majert et al.[24] planned the treatment and simulated the surgical procedures with the assistance of the software before operation. Reconstructions were performed precisely as virtually planned intraoperatively and all patients were successfully treated. Herford et al.[25] reported a case for the reconstruction of a large orbital floor defect. They used VSP to design the surgical models and implants. VSP showed the relationship between bone and optic nerve and made the complex anatomy of the area of the zygomatic complex visible. Postoperative CT showed excellent positioning of the implant, especially when compared to the unaffected side.

Mirror image is essential for patients with unilateral zygomatic complex fractures to perform surgical planning. The affected side model is obtained by mirroring the unaffected side based on the reference plane. Therefore, the establishment of the reference plane is vital to mirror imaging technique. Marmary et al.[26] reported that the midline is based on the neural foramen at the bottom of the skull. While Ogino et al.[27] reported that the midline is based on the anterior and posterior nasal processes and on the center of the left and right external acoustic foramens. Feng et al.[28] reported that the midline is based on the anterior nasal processes and on the center of the left and right condyle. According to our experience, no matter which method is referred, adjusting manually the mirrored images to fit the adjacent anatomical structures as precisely as possible is the most critical step. However, mirror imaging technique is limited to unilateral cases. In patients with bilateral zygomatic complex fractures, the surgeons must finish the virtual segmentation, osteotomy, and virtual reduction depending on their level of expertise.[21,29]

VSP provides surgeons with freedom to simulate different surgical procedures to obtain the best possible outcome for the patient, and provides new opportunities to incorporate intraoperative navigational systems which can assist in correct positioning and accurate reductions of the bony segments. Therefore, this technique is progressively becoming an indispensable part of the surgical treatment.

Rapid prototyping (RP) 3D models

RP is a generic name given to a range of related technologies that may be used to fabricate physical objects directly from computer aided design (CAD) data sources. RP enables a much quicker design and manufacture of models, compared with the traditional methods of manual prototyping.[30] It is a digital technology based on theories of discrete and accumulative forming that produces the substance layer by layer or point by point.[31] Based on the CT scan data, a skull model or a custom-designed artificial implant is built at a 1:1 scale, reproducing almost every shape of the anatomical structures.

The manufacture of 3D models can be summarized as follows: (1) acquisition of high quality scanned data; (2) 3D image processing; (3) mathematical surface modeling of anatomical surfaces; (4) formatting of data for RP (this includes the creation of model support structures which support the model during building and are subsequently manually removed); and (5) model building.[30]

The development of RP technique has been facilitated by improvements in medical imaging technology, computer hardware, 3D image processing software and the technology transfer of engineering methods into the field of surgical medicine.[30] Since first described in the 1990s, RP as a technique for manufacture of physical models from CAD/computer aided manufacturing (CAM),[32] has now been applied in a wide range of medical specialties. RP contains the following techniques: stereolithography, selective laser sintering, fused deposition, polyjet, etc. Generally, stereolithography is considered to be accurate enough and suitable for medical RP. It is one of the RP techniques used most commonly in the field of oral and maxillofacial reconstruction.[30]

Clinical applications of RP techniques in the management of zygomatic complex fractures is meaningful in the following aspects: (1) useful in preoperative simulation and to determine the validity of surgical design; (2) to predict the outcomes of surgery; (3) to help produce reposition templates or personalized preshaped implants; and (4) to guide more accurate reductions during surgery.[30,33,34] Li et al.[33] reported a patient with zygomatic-orbito-maxillary complex fracture for whom a virtual 3D skull model was produced. Design of surgical procedure, virtual surgery and final evaluation were performed on this virtual 3D skull model. The surgical procedure and postoperative effects were visualized preoperatively. Postoperative CT and images revealed significantly modified zygomatic collapse and well-modified facial symmetry. Klug et al.[10] produced a 3D skull model for each of their five cases with zygomatic fractures, for whom osteotomy and repositioning of the segments were performed using stereolithographic models. This method improved the therapeutic outcomes.

The use of 3D models can help surgeons to make a more feasible plan of surgical procedures and thus achieve better therapeutic effects.[29] Osteotomy, movement of the fractured segments, manufacture of reposition templates or personalized preshaped implants, and reduction and fixation are simulated and finished before surgery. Moreover, another advantage of using 3D models is the decreased operative time and subsequently reduced potential complications.[25]

Surgical navigation

Surgical navigation works on the basis of preoperatively acquired CT, MRI or other data. It provides continuously updated information on the position and movement of surgical instruments in the operating field corresponding to the preoperative imaging data. The information is displayed in a real-time manner on a monitor within the operating room.[35] The surgical probe can be placed anywhere on or within the patient, and the monitor will project the exact location of the probe in axial, coronal, sagittal, and 3D views.[36] In this way, the surgeons can ensure a precise location of surgical instruments or anatomic landmarks,[37] avoid damage to vital structures, and achieve the preoperatively defined reconstruction results.

The application of surgical navigation requires a number of steps: (1) acquisition of preoperative image data from patients and performance of preoperative simulation; (2) accomplishment of the patient-to-image registration process; (3) reduction and fixation of fractured segments with the guidance of navigation; and (4) evaluation and verification of the intraoperative reduction effect (Fig. 1).[38] The surgical navigation systems evolved from stereotactic neurosurgical systems (mechanical navigation devices),[14,39,40] ultrasound-based system,[14] and electromagnetic systems,[39,41] to optical navigation systems based on infrared light.[39,42,43] Surgical navigation in oral and maxillofacial surgery was first described in the 1990s for the removal of skull base tumours, foreign body extractions and the transfer of osteotomy lines.[11] Dai et al.[44] suggested that the surgical navigation system should be applied to patients with complicated diseases who require very high accuracy, such as complex zygomaxillary fractures, that necessitates a detailed preoperative VSP.

Generally, application of surgical navigation in the management of zygomatic complex fractures includes these steps: (1) verifying the effect of reduction and then adjusting the position of segments under the guidance of surgical navigation; (2) monitoring the position of the implanted orbital-wall titanium mesh in real time to reconstruct a complete anatomic structure for patients with homolateral bone defects of the orbital wall; and (3) getting accurate location of foreign bodies and removing them.[45] Westendorff et al.[35] conducted a pilot study of five patients with severely displaced orbitozygomatic fractures. All patients were treated with surgical navigation and got satisfactory results. Morrison et al.[46] reported a case of delayed reconstruction of a zygomaticomaxillary complex fracture using intraoperative navigation and showed that combining VSP with intraoperative navigation increased accuracy and shortened the operative time. Gong et al.[47] conducted a randomized clinical trial to compare the treatment effects of delayed surgery for zygomatic complex fractures, with and without a computer-assisted surgical navigation, and observed improved symmetry of facial contour in patients in the computer-assisted surgical navigation group.

The regular structure of the segments and sufficient anatomic landmarks facilitate the verification of reduction. The navigation probes are usually placed on the edges of the segments repeatedly to precisely verify the reduction until the effect of reduction is consistent with the preoperative plan.[4,48] For delayed or comminuted zygomatic complex fractures, the surface of the zygomatic bone is irregular and lacks obvious anatomic landmarks.[4] As a result, the surgeons cannot judge whether the segments have been moved to the desired position intraoperatively. Klug et al.[10] used stereolithographic models to perform virtual surgery for zygoma

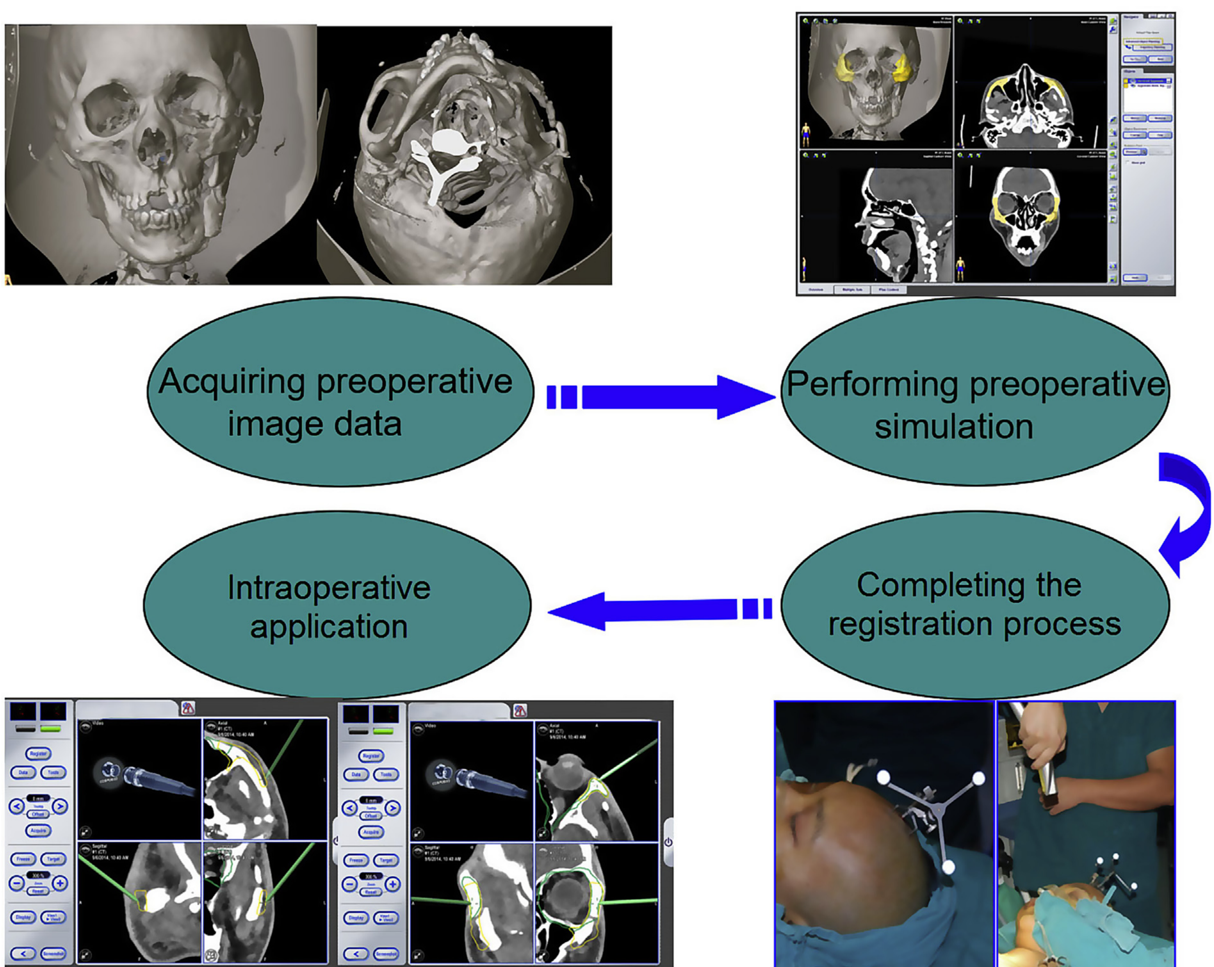

Fig. 1. The application processes of surgical navigation.

osteotomy and reduction, design preshaped plates and plan screw positions. The stereolithographic models and the patient were registered before operation. During the real operation, they used surgical navigation to locate the predetermined screw holes to regard as the landmarks for reductions and fixation. He et al.[4] created new landmarks artificially on the zygomatic bone surface in the process of preoperative software design. During the actual surgery, the location of these landmarks can be found using surgical navigation and marked by drilling holes in the zygomatic bone surface before osteotomy. This process will help locate the positions of the target bone segments accurately.

For synchronization of real-time actual surgical anatomy with the imaging of the patient's anatomic data obtained previously by CT scan, surgical navigation provides an intro-operational guide for surgeons in obtaining accurate reduction.[40,49] Successful outcomes depend on the ability to transfer the preoperative surgical plan into the actual procedures. However, the accuracy of surgical navigation can be influenced by various errors, including the image conversion, software and hardware products, data registration, and intraoperative procedures.[48,50,51] Registration is the process by which the coordinates of the image data are matched with the coordinates of the anatomical structures of the patient by navigation, and is the largest contributor to errors in image-guided operations.[52] To date, laser surface scanning (z-touch®) has been shown to be sufficiently precise for clinical deployment in previous investigations.[53,54] Based on our experience, the following tips are very effective to reduce errors. Firstly, registration references are located near to the operated area.[52,53] Secondly, the installation and fixation of the navigation reference frame must be very firm, any move or loosening should be avoided. Thirdly, scanner should be vertical to the skin during the registration. Finally, eye ointment should be chosen to replace eye masks to avoid the distortion and displacement of soft tissue.

The surgical navigation technique provides an intro-operational guide for surgeons to obtain accurate reduction, effectively avoiding damage to nearby important tissue, and tracking the anatomic position of fractured segments in real time. The surgical navigation can real-time monitor the position and depth of titanium mesh to avoid eye and optical nerve damage, which makes the operation more precise and less invasive.

Individual surgical templates and preshaped implants

Individual surgical templates are the products of CAD/CAM and a rapid prototyping technique, which can transform the simulated virtual surgical design into real surgery and bridge the virtual to the real.[55] These surgical templates are made according to the virtual surface of the zygomatic complex bones, and form a most or all framework by sticking tightly to the surface of the zygomatic complex. This framework determines the 3D space position of the complex. For the comminuted fractures or delayed fractures with landmarks destroyed, these surgical templates can directly guide the surgeons to restore the fracture blocks to the ideal position step by step.

Li et al.[55] created diverse zygomatic complex fractures types in 6 cadaver heads. Three individual templates were made in every cadaver head by CAD/CAM, and the fractures were repaired under the guidance of individual templates. Postoperative CT scans confirmed anatomic reduction in all cases. Li et al.[19] simulated the reduction of dislocated segments and preformed reposition templates and fix plates for one patient who was diagnosed with old zygomatico-orbito-maxillary fracture. At 3-month follow-up, the treatment outcome was consistent with VSP exactly. An et al.[56] manufactured two resin skull models for each patient; one of the skull models was produced by mirroring the unaffected facial side to the traumatic side. The miniplates were bended as the repositioning guide plate. During the operation, osteotomy and reduction of zygomatic and the periorbital fractures were guided by prepared repositioning guide plate. The shape and location of zygomatic bone and arch was good in one week after operation.

After the model surgery is performed on 3D model, the segments are moved to the ideal position. Given the complexity of the fractures, the available internal fixation materials may not achieve rigid internal fixation and simultaneous repair of bone defects. The preshaped titanium plates or meshes according to the post-reduction bone contours can effectively resolve this problem. During the operation, when the segments are moved to the desired position, the preshaped titanium or meshes are directly fixed firmly. At the same time, surgeons can verify whether the reduction is accurate. Feng et al.[28] made a resinous guide plate to guide intraoperative fracture reduction and preshaped titanium plates based on the preoperative 3D model to treat the unilateral malar and zygomatic arch fractures. Combined use of these techniques can increase the accuracy of the surgical procedure and improve facial symmetry.

Based on our practical experience, we usually reconstruct two skull models using a RP device. The first model is the original model obtained from CT scan data; the other model is obtained by mirroring the unaffected side onto the fractured side. The osteotomy, movement of the fractured segments, reduction and fixation are performed on the first model to simulate operation. For the second model, a reposition plate is created to guide surgical reduction and titanium plates or titanium meshes are shaped in advance to fix the fractured segments. Ultimately, an ideal template is easily put into the right position through the incision and precisely suitable for the special structure of the fractured bone (see Fig. 2).[19] Besides, the individual surgical templates also can be designed based on the VSP software without a 3D model.

The CAS technique is valuable in guiding and achieving accurate reduction. The operative time is shortened significantly. With the development of material science and medical equipment, the manufacturing costs of individual surgical templates will be reduced.

Robotic or telepresence surgery

Surgical robot is a powered computer-controlled manipulator with artificial sensing that can be reprogrammed to move and position instruments to carry out a range of surgical tasks, which extends and enhances human capabilities.[57] The incision, approach, and operation view in robotic surgery differ from existing surgical methods.[58] Due to the implement of connection between robotic system and the endoscopic, the intraoperative imaging of the patient's anatomy and the location coordinate of the robot can be fed back to the surgeons in real-time. It seems that any challenging and high-risk surgical procedures are possible by using surgical robots and telemanipulators. Robotic surgery has already been established successfully in various surgical specialties such as cardiac surgery, urology, neurosurgery and gynaecology.[59–61]

Telepresence surgery refers to the remote operation of a robot to perform a surgical procedure by the control of the surgeons. The idea of “telepresence” surgery was proposed by the National Aeronautics and Space Administration (NASA) in 1972 to provide remote surgical care to orbiting astronauts.[62] At that time, the limitations of robotic and computer systems made the development of such a system hard. Furthermore, time delay is a significantly technical problem. Subsequently, the remarkable progress in computing power and component miniaturization, coupled with the emergence of minimally invasive surgical techniques demanding complex operative procedures, the telepresence surgery has been developed quickly.

The application of robot or telepresence techniques in the management of zygomatic complex fractures should include: (1) the

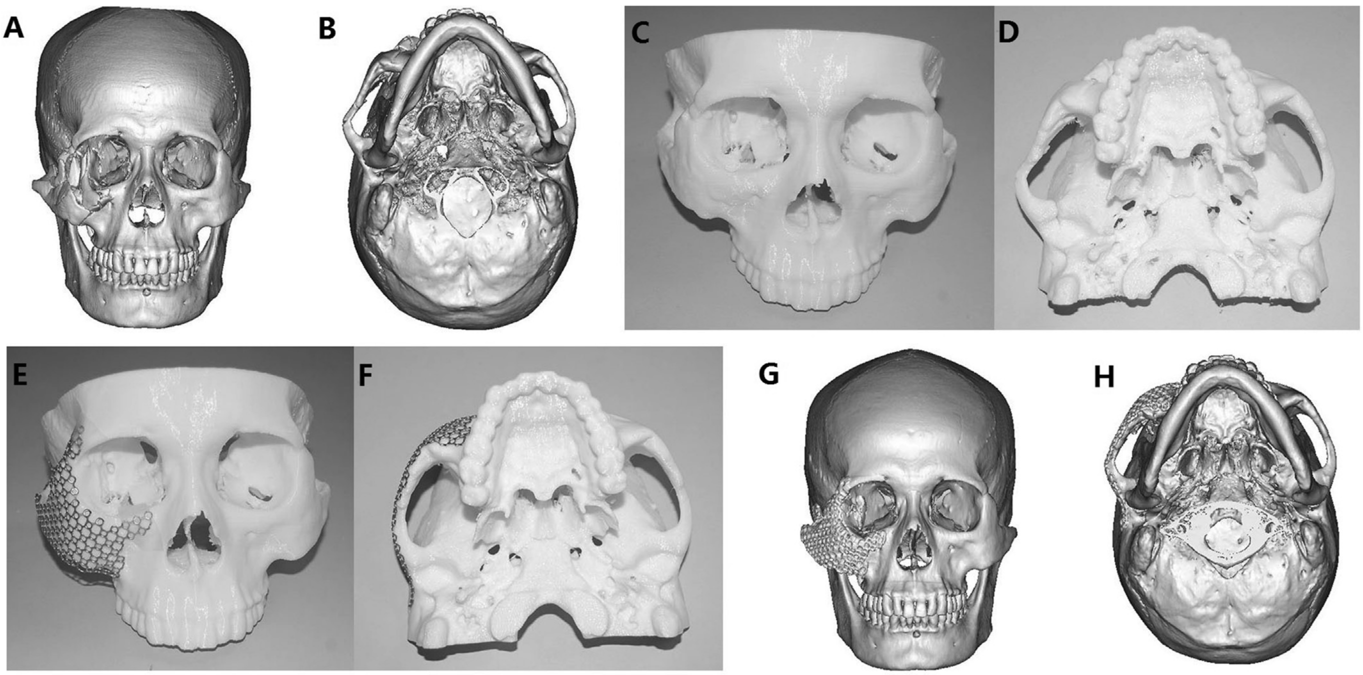

Fig. 2. A 43-year-old man was diagnosed with right delayed zygomaticomaxillary complex fractures. A, B: Preoperative imaging data with 3D reconstructions; C, D: The original model is obtained from CT scan data; E,F: The other model is obtained by mirroring the unaffected side and the titanium mesh was preshaped according to the post-reduction bone contours; G, H: Postoperative imaging data with 3D reconstructions.

drilling of holes with an automatic stop after penetrating the bone in order to protect the tissue lying deep to the bone, (2) the osteotomy and shaping of the bone segments according to the VSP in fractures without timely management, (3) performing deep saw cuts for osteotomies and allowing for the precise three-dimensional transposition of the subsequent bone segments, and (4) the preoperative automatic selection of the necessary osteosynthesis plates, their bending by a special machine and their intraoperative positioning in defined positions.[14] So far robotics in the management of zygomatic complex fractures is only in the beginning.

Robotic surgery with the da Vinci® Surgical System (Intuitive surgical, Sunnyvale, USA) is promising for the use in oral and maxillofacial surgery. The da Vinci® Surgical System consists of a surgeon's console, a surgical cart, a manipulator unit with two laterally placed instrument arms, and a centrally located endoscopic arm holding the 3-dimensional camera.[63] This system has some advantages for surgeons, like clear visual field of operation, high accuracy and flexibility, good operability, enhancement of motion scaling and tremor filtration, which improves the treatment outcomes.[62] However, in surgery the environment is often far less structured than in industry, highlighting some of the weaknesses in current robotic devices, such as substantial loss of force feedback (haptics) and a lack of adaptability. Furthermore, time delay is a substantial problem. The promise of robotic or telepresence surgery is to eliminate these impediments with the development of computer software engineering.

Conclusion

The CAS techniques are able to assist in the optimizing of operation planning, accurate location of segments intraoperatively, reduction of operation complications, and prediction of surgical outcomes.[12–14] Therefore, the CAS techniques will become an indispensable part of surgical therapy in the treatment of zygomatic complex fractures.

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