Prospects of Robot-Assisted Mandibular Reconstruction with Fibula Flap: Comparison with a Computer-Assisted Navigation System and Freehand Technique

Jian-Hua Zhu, MD[1] Jiang Deng, MD[2] Xiao-Jing Liu, MD[1] Jing Wang, MD[1] Yu-Xing Guo, MD[1] Chuan-Bin Guo, MD[1]

[1] Department of Oral and Maxillofacial Surgery, Peking University School and Hospital of Stomatology, Beijing, People's Republic of China
[2] Department of Oral and Maxillofacial Surgery, The Affiliated Hospital of Stomatology, Chongqing Medicine University, Chongqing City, People's Republic of China

Address for correspondence Chuan-Bin Guo, MD, PhD, Department of Oral and Maxillofacial Surgery, Peking University School and Hospital of Stomatology, No.22 Zhongguancun South Avenue, Haidian District, Beijing 100081, People's Republic of China
(e-mail: guodazuo@vip.sina.com).

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Abstract

Background Function and aesthetics have a significant impact on the quality of life in patients undergoing mandibular reconstructive surgery, but achieving satisfactory results remain challenging. The aim of the study is to investigate the feasibility and accuracy of robot-assisted mandibular reconstruction with fibula flap in comparison to that with a computer-assisted navigation system and the freehand technique.

Methods Experimental procedures (15 phantom studies and 6 animal experiments) were performed with a custom three-arm robotic system automatically, under the guidance of a computer-assisted navigation system, and by the freehand technique, respectively. The accuracy of the reconstruction was assessed by comparison between the preoperative and postoperative three-dimensional surface virtual models.

Results All procedures were successfully performed. In the phantom study, the mean deviation of the fibula implant was 1.221, 1.581, and 2.313 mm, respectively, with the robotic system, the navigation system, and the freehand technique; in the animal experiment the corresponding figures were 1.7697, 1.7847, and 2.0815 mm, respectively. The mean deviation of the proximal mandibular ramus was 1.0420, 1.0532, 1.8800 mm with the robotic system, computer-assisted navigation system, and freehand technique, respectively, and the mean deviation of the distal mandibular segment was 1.1645, 2.7198, and 2.8445 mm, respectively.

Conclusions The robotic system is feasible, efficient, and reliable for mandibular reconstruction. The accuracy of the fibula implant orientation with the robotic system was comparable to that with navigation system and superior to that with the freehand technique.

Keywords
- ► computer-assisted surgery
- ► robot
- ► mandibular reconstruction

Mandibular defects are commonly seen by the oral and maxillofacial surgeons as the result of the resection of tumor, severe trauma, and osteonecrosis.[1] The mandible has aesthetic value and is essential for functions such as mastication, deglutition, and articulation. With the development of the microsurgical technique, the mandibular reconstruction has become possible, but remains technically challenging because of the defect of various components. The goal of osseous

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reconstruction is to restore mandibular continuity and to correct contour.[2] A free fibula flap is routinely used as a replacement for the missing mandibular segment, and its accurate orientation and positioning contributes considerably to the restorative effects.[3] In conventional surgery, to shape and stereoposition the fibula flap, a template is manually molded intraoperatively to suit the contour of the native mandible, guided solely by the surgeon's judgment and experience.[4] Although this method is practicable, it is time taking and does not guarantee accuracy; poor accuracy results in postoperative complications, such as malocclusion and temporomandibular disorders.[3,4] Matros et al[5] evaluated the acrylic templates used in the mandible reconstructions and concluded that a standard template could be realizable for most mandible reconstructions saving the preoperative imaging and the cost of manufacturing custom cutting guides; the measurements may differ from different races and it can't meet the need for individual and accurate restorative effect.

Currently, computer-based surgery, with virtual presurgical planning, intraoperative navigation, computer-aided design/computer-aided manufacture (CAD/CAM), and rapid prototyping (RP) is increasingly being applied in the field of maxillofacial reconstructive surgery, with consequent improvements in the aesthetics and postoperative function.[3,6–10] Computer-assisted surgery enables faster, more precise, and safer reconstruction, where the virtual environment permits ideal preoperative planning and the navigation system facilitates the translation of the three-dimensional (3D) plans into accurate results in the operating room.[6,8–10] However, although the existing technologies offer significant advantages, the actual reconstructive procedure can still pose challenges unanticipated during the simulation. It is difficult to reproduce the intricate 3D conformation of the mandible, and any aberration of the movable condyle may cause mandibular location floating, particularly for the anterior defects.[10] In addition, conventional reconstructive surgery engages two groups of surgeons and usually lasts at least 7 hours. In consideration of the limited manual accuracy and manpower resource, robot-assisted surgery, which is emerging as an alternative, does not require the presence of many surgeons and is unaffected by factors such as fatigue or hand tremor.

In 1991, Taylor et al performed the first orthopedic surgery for hip replacement using the ROBODOC surgical system (Integrated Surgical Systems, Davis, CA), which was the first system that could implement a preplanned milling trajectory.[11] In oral and maxillofacial surgery, the first application of robot-assisted surgery was by Kavanagh, who performed preclinical tests of antrostomy using the ROBODOC system.[12] In 1998, the OTTO system (Surgical Robotics Laboratory, Medical Faculty Charité, Humboldt-University, Berlin, Germany) was developed as the first interactive robotic system for the use of positioning the electric drill in maxillofacial surgery.[13] To date, robot-assisted techniques have since been applied in oral and maxillofacial surgery for various procedures, for example, in transoral robotic surgery, for cutting or drilling bone for craniotomy, and for dental implantology.[14–16] To the best of our knowledge, no robotic system has been specifically designed for craniomaxillofacial reconstruction particularly in hard tissue surgery. In this study, we developed a robotic system integrating surgical planning, intraoperative navigation, and robotic assistance for mandible reconstruction, and verified its feasibility and accuracy for mandibular reconstruction in both phantom study and in animal experiment, comparing it with a computer-assisted system and with the conventional freehand technique.

Materials and Methods

Robotic System

The robotic device consisted of a custom robot device, a haptic device (Omega 6; Force Dimension, Nyon, Switzerland), an optical tracking system (Polaris; Northern Digital Inc., Waterloo, Canada), and workstations for surgical planning and robot control (►**Fig. 1**). The robot had parallel kinematics with three 7-degrees-of-freedom (DOF) arms; two of the arms were employed to grip and stabilize the residual mandible during reconstruction, while the third arm transferred the fibula flap to the receiving area. A brake pedal was introduced as an emergency switch that could cut off the power to the robot in case of any accident, stopping movement of all components of the system within milliseconds. The robotic system was designed to run automatically or with manual control. The Omega 6, a sensitive force-torque transducer with 6 DOF, was selected for master–slave control to adjust the trajectory and velocity of the robot's arms if necessary. To reproduce the virtual planning during surgery, we introduced an optical tracking system to guide the placement of the fibula implant. The optical tracking system had 0.35 mm positioning accuracy and a 20 Hz update rate. Position and orientation of end effectors and patient were tracked with the dynamic reference frames (DRF) with retroreflecting spheres that were rigidly attached to the robot and patient. Intraoperative control of this robotic system was achieved by a custom user-friendly graphical user interface that kept track of the workflow, which is necessary to simplify the procedure and guarantee the safety. Along with the robotic application controller, a custom surgery software system was also developed for 3D image reconstruction, preoperative surgical planning, and intraoperative real-time navigation. The surgery software system and the robot controller displayed on another workstation were interconnected through the local area network. With real-time guidance provided by the optical navigation system, the robot achieved accurate positioning and orientation of the implant through slow, steady movements.

Workflow

In this project, three different technologies were used for mandible reconstruction; they are described below.

1. Robotic surgery
    a. **Image acquisition**: Spiral computed tomography (CT) scan was performed with 1.25 mm slice thickness. Imaging data were converted to DICOM (digital imaging

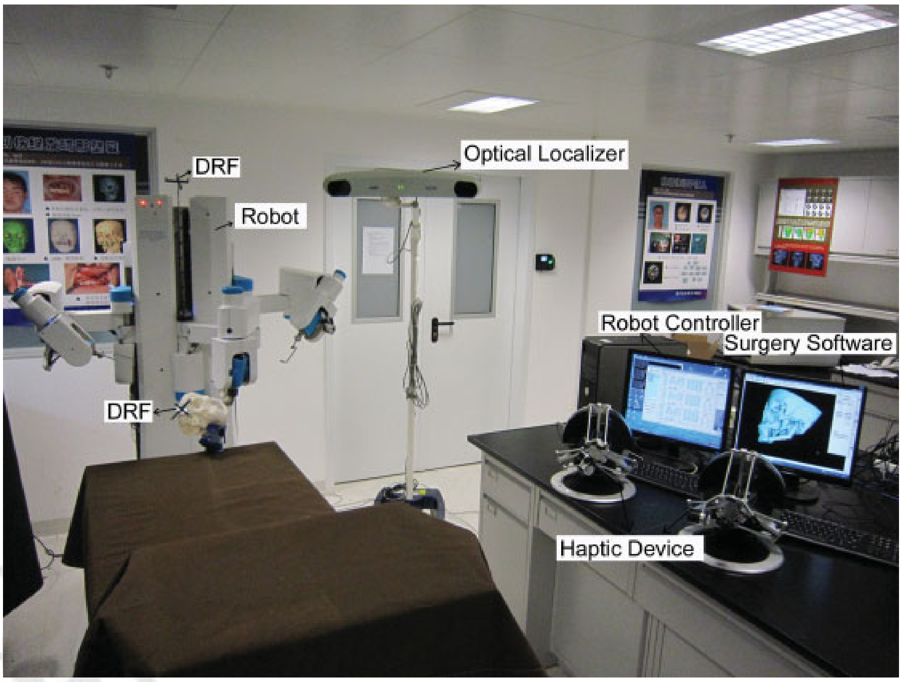

Fig. 1 Overview of the robot system.

and communications in medicine) format for 3-D reconstruction, registration, and surgical planning.

b. **Virtual surgical planning**: After segmentation through the CT image data, a surface model of the skull with the defected mandible was created by the surgeon during virtual surgical planning. Subsequently, with 3D visualization of the skull, the position and orientation of the fibula implant was planned before surgery.
c. **Navigation registration**: The intraoperative navigation system and the robot were initialized first. Seven titanium screws were inserted in the maxillofacial region as markers, with which the registration of images to the patient was achieved by means of the pair-point method through an improved iterative closest point (ICP) algorithm. The registration of the navigation system to the robot was also performed by the point-based method. With the DRF rigidly attached to the patient and the robot, their position was tracked by the navigation system in real-time. Four titanium screws were inserted into the fibula implant as markers, and the registration of the implant to the navigation was realized by probe pointing. The navigation system was used as an intermediate coordinate to align the different components. The robot, patient, fibula implant, and images were then correlated by matrix transformation. The intraoperative osteotomy lines were confirmed to create mandible defect by accurate navigation after registration and fibula flap was shaped in the light of virtual surgical planning.
d. **Robot-assisted positioning**: Once the preoperative planning was transferred to the robot controller, the intraoperative position data of each of the joints of the three arms was determined after registration. The left and right arms were used to clamp and rigidly hold the remnant mandible after osteotomy lines were verified to perform mandible resection, while the middle arm, with the end effector gripping the fibula implant, brought the implant to the designed reconstructive site automatically and precisely under navigation or, if necessary, under manual control.
e. **Fibula fixation**: The surgeon used titanium plates and screws to fix the fibular implant to the remaining mandible, while the robot arms held them rigidly in place.
f. **Postoperative imaging**: Postoperative CT scanning of the skull was performed with the same scanner. The preoperative and postoperative 3D virtual models were imported to the analysis software for comparison.

2. Computer-assisted navigation surgery
Based on the imaging data of the defected mandible, mandible reconstruction was manually performed, guided by computer-assisted navigation. Image acquisition, surgical planning, and navigation registration were the same as described for robotic surgery. The other steps of placing the fibula implant were performed as follows:
   a. **Navigation positioning**: The navigation probe was pointed at the screw marker inserted in the fibula implant. The positional relationship between the skull and the fibula implant was manually adjusted by relative motion with image guidance. The connection of the probe tip with the screw marker was maintained until the corresponding points in the image space were found. Thus, we located all the markers as planned in the image space to confirm that the position and orientation of the implant was correct.

Fig. 2 Mandible reconstruction in phantom study with robotic surgery (**a**), computer-assisted navigation surgery (**b**), and manual surgery (**c**).

   b. **Fibula fixation**: Once the fibula implant was in position, the assistant held the mandible steady, while the titanium plates were bent to conform to the shape of the reconstructed mandible, and the plates were then screwed into place. After the implant was firmly fixed, the position of the screw markers was verified again by the probe.

3. Freehand surgery

In the conventional surgery, all steps were performed by the surgeon based on direct measurements and his/her experience and judgment. The procedure was as follows:

a. **Fibula preparation**: The mandible defect was created according to the preoperative planning. The range of the mandible defect was evaluated by using a calibrated splint or ruler, following which the fibula implant was manufactured.
b. **Fibula placement**: To maintain the continuity and contour of the mandible, the position of the fibula implant was manually adjusted in the reconstructive site and when visual feedback suggested that the reconstructive effect was adequate, the implant was fixed in place.

Phantom Study

Based on CT data of the human skull, the reconstruction of the defected mandible with the fibula implant was planned. With stereolithography (STL) data sent to the 3D printer (ProJet 1500; 3D Systems; Rock Hill, SC), we manufactured 15 sets of RP models of the defected mandible and the fibula implant. They were evenly divided into different groups. Titanium screws of 2 mm diameter (Synthes, Solothurn, Switzerland) were inserted into the skull ($n = 7$) and the fibula implant ($n = 4$) as registration markers. Subsequently, CT data (1.25-mm slice thickness; Siemens, Germany) was acquired by scanning the marked mandible and fibula models for surgical simulation. The surgical procedures were then performed with the three different technologies (►**Fig. 2**).

Postoperative CT images were acquired with the same scanning parameters. After segmentation of the skull, the preoperative and postoperative 3D surface virtual models in STL format were imported into the analysis software Geomagic Studio 12.0 (Geomagic Inc., Morrisville, NC), which transformed the 3D surface data into 3D point cloud data. The software automatically superimposes the 3D objects representing the postoperative surgical outcome onto the preoperative virtual plan. The point-to-point alignment technique can then be used to compare the points located in selected region between the virtual plan and the final result (►**Fig. 3**).

Animal Experiment

Six animal experiments were performed with the three different technologies. The experimental sheep were provided by the Experimental Animal Center of the Stomatology Hospital of Peking University. This study was reviewed and approved by the Ethics Committee of Peking University School and Hospital of Stomatology. The operations of all

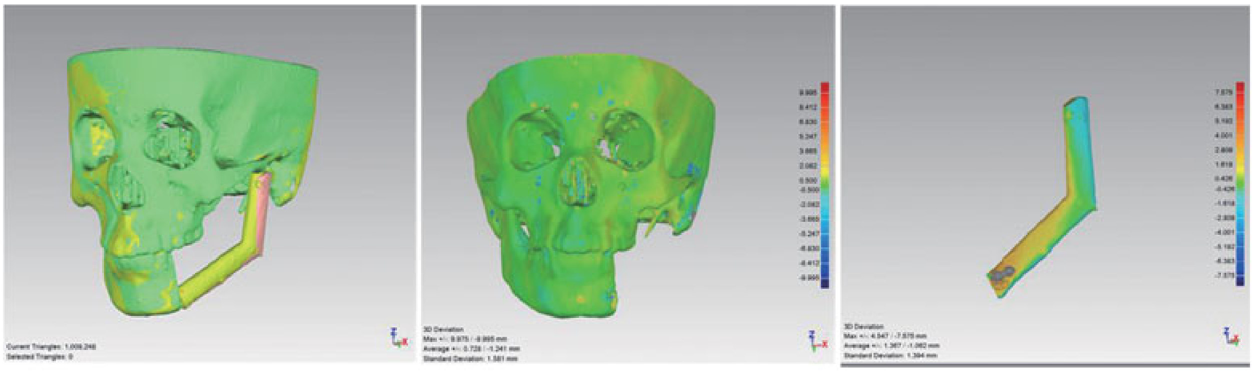

Fig. 3 The comparison between the virtual and the final 3D model demonstrated in chromatographic image in the phantom study. 3D, three-dimensional.

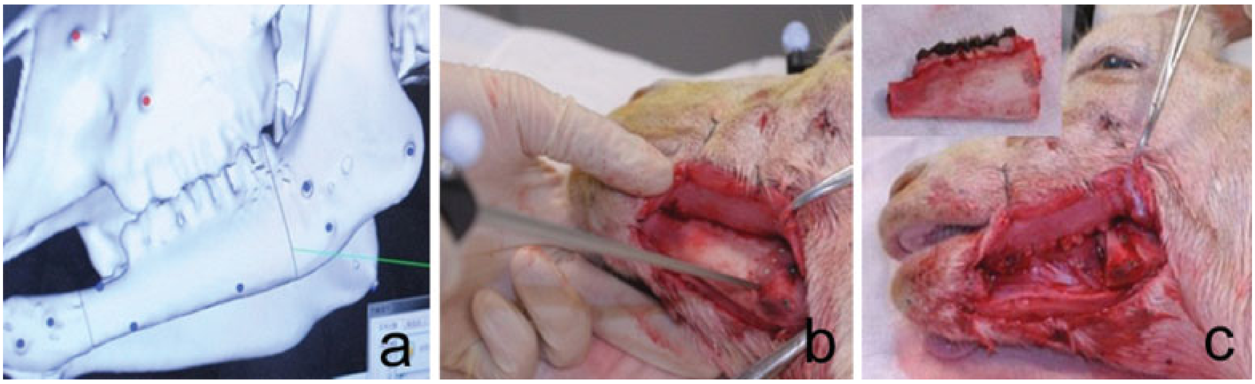

Fig. 4 The model of the mandible defect created under navigation: (**a**) The virtual osteotomy line, (**b**) confirmed the planned line during operation, (**c**) osteotomy was performed.

experiments were strictly in accordance with the animal ethical standards. Each sheep was kept in an ideal anesthetic state during surgery.

For robot-assisted and computer-assisted navigation surgery, titanium screws were inserted into the craniomaxillofacial skeleton of the sheep as fiducial markers. CT scan was then performed for each marked sheep. With segmentation from the CT data, a surface model of the sheep skull was reconstructed. The mandible osteotomy was planned on the surface model, using a virtual scalpel in the custom surgical planning and simulation system. To restore the continuity of the mandible, 3D STL marked fibula models corresponding to the mandible defect were printed out by the RP technique. After point-to-point registration, the segmental osteotomy was accurately positioned on the sheep mandible under navigation, where the cutting trajectory was directed by preoperative plans. The resulting model of the defected mandible of sheep is shown in ►**Fig. 4**. For freehand surgery, the mandible defect was achieved by manual operation, and the fibula implant was shaped by the surgeon based on his/her personal judgment/experience. Reconstructive surgeries were performed by the different technologies as described previously (►**Fig. 5**). As before, postoperative results were compared with the preoperative plan (►**Fig. 6**).

Results

All mandibular reconstructions were successfully performed and the results were shown in ►**Tables 1** and **2**. The robotic system functioned normally and stably. In the phantom study, the mean deviation of the fibula implant was 1.221, 1.581, and 2.313 mm, respectively, with the robotic system, the navigation system, and the freehand technique; in the animal experiment the corresponding figures were 1.7697, 1.7847, and 2.0815 mm. The mean deviation of the proximal mandibular ramus was 1.0420, 1.0532, 1.8800 mm with the robotic system, computer-assisted navigation system, and freehand technique, respectively, and the mean deviation of the distal mandibular segment was 1.1645, 2.7198, and 2.8445 mm, respectively.

Discussion

Function and aesthetics are important determinants of quality of life in patients undergoing reconstructive surgery, but achieving satisfactory results can be challenging.[17] Current advances in 3D imaging, navigation system, CAD/CAM techniques, STL models, and RP techniques allow reconstructive surgery to be performed rapidly and accurately.[3,17–19] In soft tissue surgery, navigation-guidance may not provide optimal results because of the problem of tissue drifting, but this is not an issue in hard tissue surgery.[17] Nevertheless, whereas robotic surgery has been used for the soft tissue free flap reconstructions,[20,21] its application in craniomaxillofacial bone defect reconstructions is still a novelty. Positioning tools precisely at a preplanned site or moving them through a complicated trajectory is one of the developmental purposes for robotic surgery.[22] Surgical robot systems permit virtual preoperative planning to simulate surgical outcome in advance, with ability to move stably to and within the target areas to transfer the scheme accurately to the operation.[23] The passive manipulators are cumbersome and, with the attached tools, have limited workspace; however, they are unaffected by issues such as hand tremors or line-of-sight problems, and offer advantages such as the ability to lock tools in position.[22] The combination of the robotic system with a navigation technique offers tremendous promise, allowing steady movement and accurate positioning, which can improve the accuracy of mandibular reconstruction and reduce complications related to limited manual accuracy.

A surgical robot is defined as a powered, computer-controlled manipulator with the capability of sensing and reprogramming motion, which makes it distinguished from computer-assisted surgery and the surgeon.[22] In recent years, preprogrammed robotic systems such as the Robodoc system (Integrated Surgical Systems, Davis, CA), the Acrobot system (Acrobot Company Limited, London, England), and the RobaCKa system (University of Karlsruhe, Karlsruhe, North Dakota, Germany) have been developed for accurate bone milling along planned trajectories in orthopedics or craniofacial surgery.[15,16,23,24] Such robots make movements only after the surgeon's confirmation or, alternatively, they move passively under the control of the

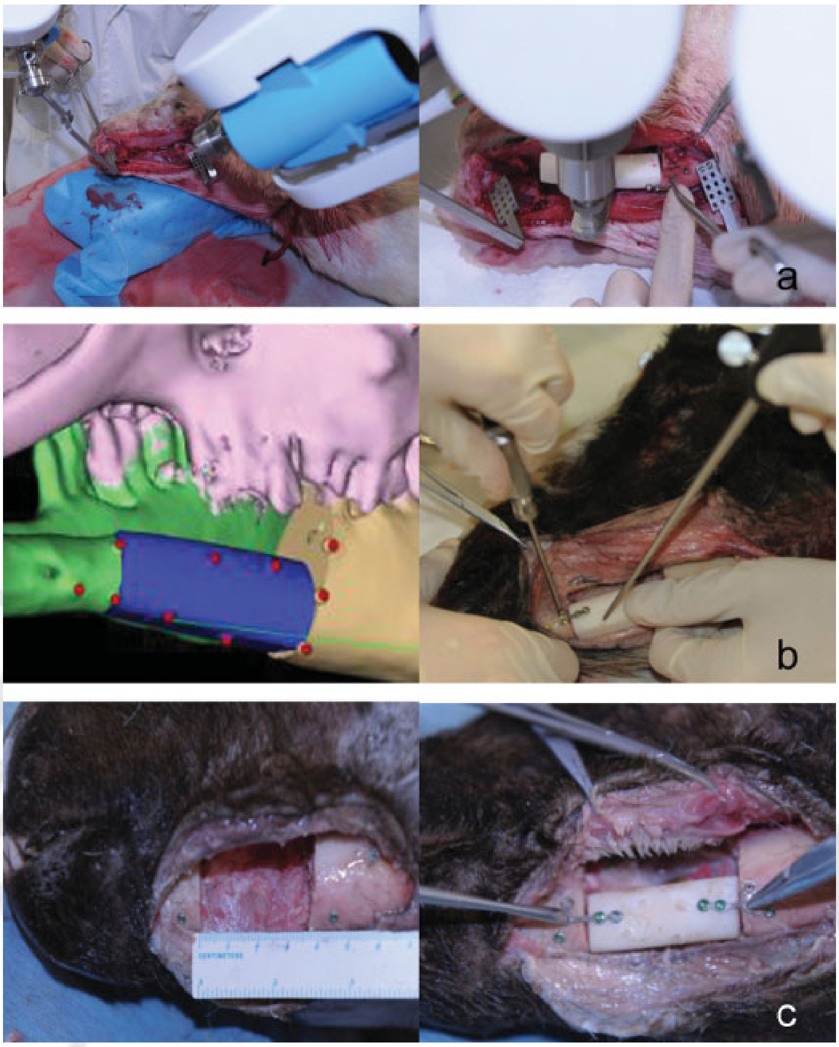

Fig. 5 Mandible reconstruction in animal experiment with (**a**) robotic surgery, (**b**) computer-assisted navigation surgery, (**c**) and manual surgery.

surgeon, with a force-torque sensor, such as the haptic device used in this study, to provide feedback; they do not replace the surgeon, but work as an assistant under supervision.[22] In this system, therefore, the placement of the fibula implant can be performed automatically by the robot, provided that the trajectories match the trajectories in the preoperative planning. The lack of the feedback is the bottleneck for the application of robotic surgery. Although visual feedback can compensate for this, haptics is still important for safe surgery and reduction of postoperative problems.[22,25,26] With the development of microforce sensors, haptic devices have become available. Our robotic system was unique to the commonly used systems such as the Da Vinci system (Intuitive Surgical Inc., Sunnyvale, CA) and the ZEUS system (Intuitive Surgical Inc.) by the introduction of the Omega 6, an advanced force feedback device with 3 DOF for position and 3 DOF for orientation, for master–slave control. This allowed the surgeon to sense any errors in position or orientation with the manner of exchanged mechanical energy and halt or slow down the robot's movements accordingly, and thus increased safety, especially during operations in vulnerable areas. Wurm et al[27] used the Mitsubishi's RV-1a articulating arms, robot with 6 DOF to perform paranasal sinus and skull base surgery, guided by a navigation system (Mitsubishi Electric, Tokyo, Japan). Their robot had an integrated force-torque sensor that could send feedback to the operator's hands; this allowed the stereotactic error to be reduced to < 1 mm. To operate the complex surgical process, three flexible arms with 7 DOF were collocated in this system, giving the surgeon the incomparable ability of manipulating more than two arms and thus allowing the surgeon to become his/her own assistant.[28] Despite the drawback of parallel kinematics is the limitation in motion workspace, this limitation does not affect the performance of mandibular reconstruction for the need of an only confined workspace; besides, improved accuracy and steadiness of motion are obvious advantages.[23]

To acquire an optimal outcome in mandibular reconstruction, favorable anteroposterior and transverse relationships have to be achieved by precise placement of the fibula implant, which needs to be connected to the contralateral side at the correct occlusal plane angle.[19] In this study, both in the phantom study and the animal experiment, the pose of the fibular implant was more accurate with the robotic system and computer-assisted navigation than with conventional manual surgery. The accuracy achieved in the phantom

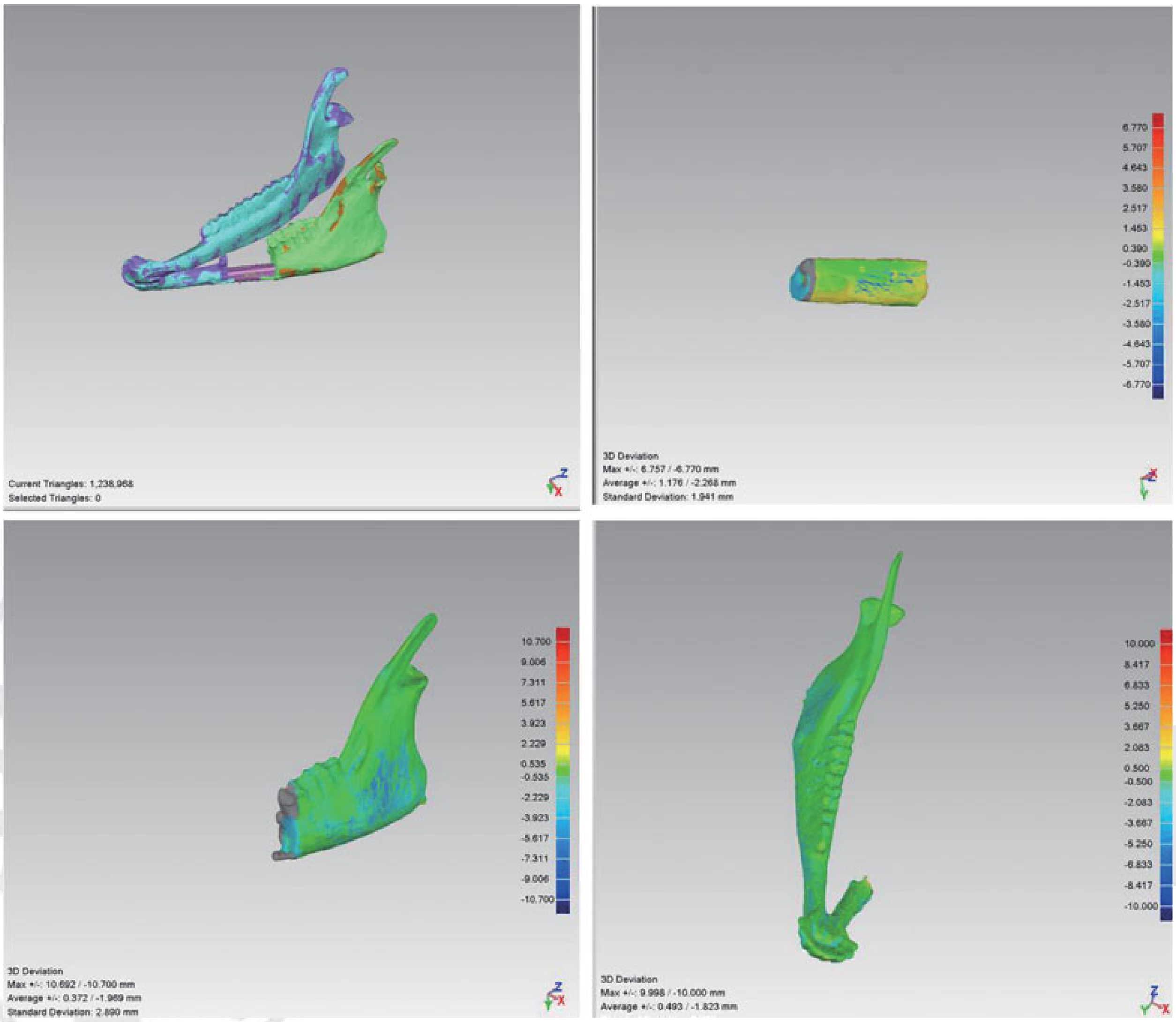

Fig. 6 The comparison between the virtual and the final 3D model demonstrated in chromatographic image in the animal experiment. 3D, three-dimensional.

study was superior to that in the animal experiment with the robotic system and computer-assisted navigation; this is to be expected because the mobile articulations and muscle attachments in the animal model affect the position of the mandible. Unexpectedly, the manually implanted fibula showed slightly larger deviations in phantom study than in animal experiment; a plausible explanation could be that the residual mandibular ramus had contributed to the position and orientation of the fibula implant with freehand technique in the animal experiment. There was little difference in precision between robotic surgery and navigation surgery in this study. During actual surgery, the distinction between robotic surgery and navigation surgery would most likely be highly significant because the human mandible convexity is more complex and it is impossible to pose the skull at arbitrary angles in the operation room; robotic surgery compared with navigation surgery and manual surgery, however, offers this unparalleled advantage: the ability to rigidly clamp the free-floating native mandible and tirelessly maintain it in position with multiple arms as an assistant. Any component of the system can contribute to the cumulative deviance from the planned result: problems may arise from image distortion, optical localizer error, inherent kinematic limitation, the limitations of the computer control algorithm, registration error, and human error. Although it is not practical to separate all the possible influencing factors and to quantify them, the overall registration error is one of the most significant factors in both computer-assisted surgery and robotic procedures, particularly in the navigation of a mobile structure such as the mandible.[22] For the spatial registration of the three-arm robot, the hand–eye coordination was based on an improved ICP algorithm; with this approach the position error can achieve below 1 mm.[29] For the registration of image to the patient, the paired-point registration shows the best registration accuracy in the craniomaxillofacial application,[30] but its accuracy in the mobile mandible has not yet been adequately studied. A special sensor frame mounted onto the mandible is an alternative to optically track the jaw's position and to compensate for its intraoperative random movement.[19] Bone fiducials is the current gold standard for

Table 1 Deviation of fibula implant in phantom study with robotic surgery, computer-assisted navigation surgery, and manual surgery, respectively

Phantom study	Deviation (mm)		
	Robotic surgery	Computer-assisted navigation surgery	Manual surgery
Fibula implant	1.285	1.564	2.515
	1.153	1.612	2.418
	1.297	1.589	2.553
	1.215	1.510	1.967
	1.157	1.631	2.110
Mean value	1.221	1.581	2.313

paired-point registration, providing higher accuracy than skin fiducials and anatomic landmarks.[31] As Bao et al[32] advised, with the nonlinear arrangement of enough fiducial markers and extensive distribution of fiducial markers around the target, it is possible to get excellent registration accuracy. Therefore, we had seven titanium screws distributed around the skull to serve as fiducial markers in this study. The precision of manual bending of the miniplates is another nonnegligible factor, which indirectly determines the positional relationship of the fibula implant between the proximal mandibular ramus and the contralateral segment. The CAD/CAM reconstruction plates manufactured by 3D printers are promising substitutes that can provide high position accuracy and stability of the fibular segments.[33]

The present study has several limitations. First, this was a preliminary study with only a modest number of phantom models and animal trials. Further studies in larger sample are required to confirm the superiority of the robotic system in mandible reconstruction, even in preclinical studies. Second, the insertion of markers for registration is an invasive procedure. Noninvasive methods such as surface matching should be developed, which would be technically easier and also be applicable in emergency cases when necessary. Invasive markers are attached to the skin or an external referencing frame as fiducials, which is an alternative according to the universal practice. In clinic, it is not practical to perform CT scanning after the screws were inserted to the fibula and mandible. A custom guide plate, designed with virtual localization marker of the screws inserted in the fibula according to the preoperative CT data, can be used to help surgeons out during the operation. Surgeons can confirm the placement of the fibula by the comparison of the planned localization of the virtual markers with the screws inserted under the guidance of the custom plate. Actually, in consideration of the limitation of initial phantom studies and animal experiments, if the robot can be used in the clinic, it is not necessary to confirm the reposition of the fibula by the screw fiducials every time during the operation in the future. Last but not the least, the current robot only serves as an auxiliary position device for mandible reconstruction. The potential for performing precise, deep saw cuts for osteotomies, with reprogrammable constrained motions, needs to be developed to prevent damage to vital regions.

Table 2 Deviation of fibula implant, the proximal mandibular ramus, and the distal mandibular segment in animal experiment with robotic surgery, computer-assisted navigation surgery, and manual surgery, respectively

Animal experiment	Deviation (mm)		
	Robotic surgery	Computer-assisted navigation surgery	Manual surgery
Fibula implant	1.7220	1.3940	2.4300
	1.8175	2.1755	1.7330
Mean value	1.7697	1.7847	2.0815
Proximal mandibular ramus	0.9260	0.9370	0.8660
	1.1580	1.1695	2.8940
Mean value	1.0420	1.0532	1.8800
Distal mandibular segment	1.1580	2.7665	2.6360
	1.1710	2.6732	3.0530
Mean value	1.1645	2.7198	2.8445

Conclusion

We developed a parallel kinematics robotic system for mandibular reconstruction and confirmed its efficacy and accuracy in both phantom study and animal experiment. The robotic system was able to rigidly hold the mandible rigidly in position, while precisely conveying bone segments to the reconstruction site. The accuracy of the robot system for fibula implant orientation was comparable to that with the navigation system and superior to that with the freehand technique. Further studies that are needed to confirm our results.

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References

1 Kokosis G, Schmitz R, Powers DB, Erdmann D. Mandibular reconstruction using the free vascularized fibula graft: an overview of different modifications. Arch Plast Surg 2016;43(1):3–9
2 Disa JJ, Cordeiro PG. Mandible reconstruction with microvascular surgery. Semin Surg Oncol 2000;19(3):226–234
3 Metzler P, Geiger EJ, Alcon A, Ma X, Steinbacher DM. Three-dimensional virtual surgery accuracy for free fibula mandibular reconstruction: planned versus actual results. J Oral Maxillofac Surg 2014;72(12):2601–2612
4 Tarsitano A, Ciocca L, Cipriani R, Scotti R, Marchetti C. Mandibular reconstruction using fibula free flap harvested using a customised

cutting guide: how we do it. Acta Otorhinolaryngol Ital 2015; 35(3):198–201

5 Matros E, Santamaria E, Cordeiro PG. Standardized templates for shaping the fibula free flap in mandible reconstruction. J Reconstr Microsurg 2013;29(9):619–622

6 Dérand P, Hirsch JM. Virtual bending of mandibular reconstruction plates using a computer-aided design. J Oral Maxillofac Surg 2009; 67(8):1640–1643

7 Nijmeh AD, Goodger NM, Hawkes D, Edwards PJ, McGurk M. Image-guided navigation in oral and maxillofacial surgery. Br J Oral Maxillofac Surg 2005;43(4):294–302

8 Ewers R, Schicho K, Undt G, et al. Basic research and 12 years of clinical experience in computer-assisted navigation technology: a review. Int J Oral Maxillofac Surg 2005;34(1):1–8

9 Tarsitano A, Mazzoni S, Cipriani R, Scotti R, Marchetti C, Ciocca L. The CAD-CAM technique for mandibular reconstruction: an 18 patients oncological case-series. J Craniomaxillofac Surg 2014; 42(7):1460–1464

10 Matros E, Albornoz CR, Rensberger M, Weimer K, Garfein ES. Computer-assisted design and computer-assisted modeling technique optimization and advantages over traditional methods of osseous flap reconstruction. J Reconstr Microsurg 2014;30(5):289–296

11 Taylor RH, Paul HA, Mittelstadt BD, Hanson W. An image-directed robotic system for precise orthopaedic surgery. Calixarenes Nanoworld 1994;10(3):261–275

12 Kavanagh KT. Applications of image-directed robotics in otolaryngologic surgery. Laryngoscope 1994;104(3 Pt 1):283–293

13 Lueth TC, Hein A, Albrecht J, Demirtas M. A surgical robot system for maxillofacial surgery. Paper presented at: IECON '98: Proceedings of the 24th Annual Conference of the IEEE Industrial Electronics Society; August 31–September 4, 1998; Aachen, Germany, 1998

14 De Ceulaer J, De Clercq C, Swennen GR. Robotic surgery in oral and maxillofacial, craniofacial and head and neck surgery: a systematic review of the literature. Int J Oral Maxillofac Surg 2012;41(11): 1311–1324

15 Engel D, Raczkowsky J, Worn H. A safe robot system for craniofacial surgery. Paper presented at: Proceedings of the IEEE International Conference on Robotics and Automation; May 21–26, 2001; Seoul, Korea, 2001

16 Boesecke R, Brief J, Raczkowsky J, et al. Robot assistant for dental implantology. Paper presented at: the 4th International Conference on Medical Image Computing and Computer-Assisted Intervention; October 14–17, 2001; Utrecht, The Netherlands, 2001

17 Balasundaram I, Al-Hadad I, Parmar S. Recent advances in reconstructive oral and maxillofacial surgery. Br J Oral Maxillofac Surg 2012;50(8):695–705

18 Lim SH, Kim MK, Kang SH. Precision of fibula positioning guide in mandibular reconstruction with a fibula graft. Head Face Med 2016;12(1):7

19 Bell RB, Weimer KA, Dierks EJ, Buehler M, Lubek JE. Computer planning and intraoperative navigation for palatomaxillary and mandibular reconstruction with fibular free flaps. J Oral Maxillofac Surg 2011;69(3):724–732

20 de Almeida JR, Genden EM. Robotic assisted reconstruction of the oropharynx. Curr Opin Otolaryngol Head Neck Surg 2012;20(4): 237–245

21 Garfein ES, Greaney PJ Jr, Easterlin B, Schiff B, Smith RV. Transoral robotic reconstructive surgery reconstruction of a tongue base defect with a radial forearm flap. Plast Reconstr Surg 2011;127(6): 2352–2354

22 Davies B. A review of robotics in surgery. Proc Inst Mech Eng H 2000;214(1):129–140

23 Korb W, Marmulla R, Raczkowsky J, Mühling J, Hassfeld S. Robots in the operating theatre—chances and challenges. Int J Oral Maxillofac Surg 2004;33(8):721–732

24 Jakopec M, Harris SJ, Rodriguez y Baena F, Gomes P, Cobb J, Davies BL. The first clinical application of a "hands-on" robotic knee surgery system. Comput Aided Surg 2001;6(6):329–339

25 Maan ZN, Gibbins N, Al-Jabri T, D'Souza AR. The use of robotics in otolaryngology-head and neck surgery: a systematic review. Am J Otolaryngol 2012;33(1):137–146

26 Simorov A, Otte RS, Kopietz CM, Oleynikov D. Review of surgical robotics user interface: what is the best way to control robotic surgery? Surg Endosc 2012;26(8):2117–2125

27 Wurm J, Dannenmann T, Bohr C, Iro H, Bumm K. Increased safety in robotic paranasal sinus and skull base surgery with redundant navigation and automated registration. Int J Med Robot 2005;1(3): 42–48

28 Camarillo DB, Krummel TM, Salisbury JK Jr. Robotic technology in surgery: past, present, and future. Am J Surg 2004;188(4A, Suppl) 2S–15S

29 Wang Y, Duan X. Spatial registration for a three-arm robot assistedmandible reconstruction surgery. Math Probl Eng 2015; 2015(1, part 2):1–10

30 Luebbers HT, Messmer P, Obwegeser JA, et al. Comparison of different registration methods for surgical navigation in cranio-maxillofacial surgery. J Craniomaxillofac Surg 2008;36(2):109–116

31 Widmann G, Stoffner R, Bale R. Errors and error management in image-guided craniomaxillofacial surgery. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2009;107(5):701–715

32 Bao N, Chen Y, Yue Y, et al. Fiducial markers configuration optimization in image-guided surgery. Biomed Mater Eng 2014; 24(6):3361–3371

33 Schepers RH, Raghoebar GM, Vissink A, et al. Accuracy of fibula reconstruction using patient-specific CAD/CAM reconstruction plates and dental implants: A new modality for functional reconstruction of mandibular defects. J Craniomaxillofac Surg 2015; 43(5):649–657