Robotics in Dental Implantology

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KEYWORDS

• Robotic surgery • Robot-assisted dental implant surgery • Navigation • Static guided surgery • Dynamic guided surgery

KEY POINTS

- An overview of robotic surgery in oral and maxillofacial surgery is presented as background knowledge for better understanding of the current development of robot-assisted dental implant surgery.
- The current status of robot-assisted dental implant surgery is evaluated and illustrated with worldwide examples.
- The advantages and limitations of the robot-assisted dental implant surgery are discussed. The latest development in autonomous robot is explored.

Robotic surgery is no longer fiction, it is a reality. This article provides an overview of robotic surgery and its current applications in oral and maxillofacial surgery and implant dentistry.

The origins of robot-assisted surgery stem from pioneering work done at the National Aeronautics and Space Administration (NASA). In the mid-1980s, NASA developed a remotely controlled robotic system to surgically operate on astronauts in space, as well as soldiers on the battlefield. Since the first robotic system for laparoscopic surgery, when the da Vinci model, with a so-called master-slave setup, was approved by the US Food and Drug Administration (FDA) in 2000, robots have been increasingly used for different surgical procedures across various surgical specialties, including urology, gynecology, and general surgery. In comparison with conventional laparoscopic surgery, robot-assisted surgery catalyzed the advance of minimally invasive surgery by incorporating real-time stereoscopic vision of the operative field, eliminating the detrimental effect of hand or instrument tremors, and allowing for instrumentation with a freedom of movement and precision beyond that of a surgeon's hand and wrist. As a result, a robotic system provides an easy-to-use platform offering increased maneuverability for a surgeon and an improved working environment for the entire surgical team.

The master-slave setup consists of a surgeon console (master unit) and a system of robotic arms (slave unit). In 2001, the master-slave setup concept was validated by a transcontinental live robotic cholecystectomy. That was the first time

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that a patient in a location was operated by a team of surgeons elsewhere (telepresence).

Despite many documented advantages, robotic surgery is associated with certain challenges. In several studies comparing conventional laparoscopic surgery and robotic surgery, robotic surgery was more resource-demanding. Operation times using a robotic system were prolonged and the costs of robotic surgery were more expensive.[1,2] Last, but not least, robotic surgery has a steep learning curve.[3] To master robotic surgical techniques, it is essential for surgeons to acquire a set of core skills. It has been shown that these core skills are independent of the surgical procedures. Liu and Curet[4] reported that these core skills are divided into 2 categories: (1) skills to control the console and (2) psychomotor skills for robotic surgery.

To control the robotic arms effectively, the operator of the robotic system needs to learn how to perform the surgical procedures in the console, which means that while surgeons are performing bimanual wrist manipulation for the robot-assisted surgery, they also need to know how to control the stereoscopic camera, to master clutching, to change the robotic arm position, and to activate energy sources simultaneously. The psychomotor skills include correct depth perception in relation to stereoscopic vision and an appreciation of force applied to the robotic instruments through the robotic arm.

The success of robotic surgery requires both a trained and skillful surgeon and a capable team of assistants, nurses, and anesthesiologists. The surgeon is physically away from the surgical field, separated from the rest of the surgical team, and is fully occupied when operating in the isolated console. To ensure optimal team dynamics and to shorten reaction time in response to any complications arising during operation, effective team communication and collaboration should be developed through simulation-based team-based learning. Liu and Curet[4] recommended that experts from the clinical, educational, and technological fields work together to design a simulation training platform for robotic surgery.

In December 2009, the da Vinci system received FDA approval to be used for transoral procedures in all benign diseases and selected malignant lesions of the oropharynx, including the base of tongue and larynx. Transoral robotic surgery (TORS) is defined as robot-assisted surgery performed on the upper aerodigestive tract accessed through the oral cavity.

Malignant tumors arising from the oropharynx are surgically inaccessible in many instances. Therefore, chemotherapy and/or radiotherapy are usually the primary treatment modalities. When salvage surgery is considered, it is commonly performed via a mandibulotomy with lip split and mandibular displacement. TORS, with its robotic arms, multiarticulated instruments, and stereoscopic vision, allows surgeons to operate in this difficult area with minimal invasiveness. It has been shown that excellent local control can be achieved by robotic surgery in patients with low-risk oropharyngeal squamous cell carcinoma.[5]

In addition to the management of pathologic conditions, TORS is increasingly used for surgical management of obstructive sleep apnea (OSA). OSA is classified as mild, moderate, or severe based on the apnea-hypopnea index (AHI). OSA is associated with increased morbidity and mortality when the AHI is greater than 15. For OSA, continuous positive airway pressure (CPAP) is the standard of care. However, patient intolerance and poor compliance are significant problems with CPAP therapy. Surgical treatment of OSA includes uvulopalatopharyngoplasty, tongue base resection using CO2 laser or radiofrequency, hyoid bone suspension, maxillomandibular osteotomies for jaw advancement, weight control and bariatric surgery in morbidly obese patients, and so forth. The outcomes of these surgical techniques are inconsistent because airway obstruction in patients with OSA is usually found at multiple levels. However, meta-analyses indicate that maxillomandibular advancement (MMA) can achieve a high success rate of 86% to 100%.[6,7] Despite the effectiveness of MMA, there are patients who may benefit directly from tongue base reduction.

TORS for the treatment of OSA was first reported in 2010 by Vinci and colleagues.[8] In their preliminary report with 10 subjects, they investigated the efficacy of tongue base reduction with TORS and demonstrated that the robot-assisted procedure was well-tolerated by patients and yielded minimal morbidity. In addition, significant improvement in AHI was found in all 10 subjects.

Robotic surgery is constantly evolving and its applications are continuously expanding. Recently, robot-assisted surgery has been used for dental implant placement. In the United States, the first robotic dental surgery system, Yomi (Neocis Inc, Miami, FL, USA), was cleared by FDA for dental implant procedures in 2017. This first system provides software for planning and navigational guidance for instrumentation during implant surgery. The system also delivers haptic feedback and controls the position, depth, and angulation for implant osteotomy. However, the cost-benefit and cost-effectiveness of robotic surgery in implant dentistry is significant and awaits validation.

As previously mentioned, robot-assisted surgery is resource demanding and has a steep learning curve. Therefore, the quest for autonomous surgical robotics is ongoing. With the advancements in surgical navigation and artificial intelligence, autonomous robotic surgery is already under development.

ROBOT-ASSISTED MANUFACTURED SURGICAL TEMPLATE

Use of a surgical guide template is considered a reliable strategy to assist in diagnosis and facilitate proper position of implant placement according to the prosthesis design. However, the error of surgical templates, such as vacuum-formed templates, cast-based surgical guides, and computed tomography (CT)-generated static guides, depends on the manufacturing method and design. To minimize error, research has focused on assessing the technical precision of robot-assisted static guided manufacture. Julien Dutreuil and colleagues[9] described an accurate robotic experience to prepare an osteotomy site in an edentulous mandible model using a surgical guide and a virtual fixture. The robot provided a plus or minus 0.04-mm translation accuracy and a plus or minus 0.15° rotation accuracy with 5 degrees of freedom (DOF), and was used to drill a jaw splint according to virtual implant location after registration between the robot and software able to interpret radiopaque balls. Studies from Fortin and Vercruyssen,[10,11] a method of transferring image data into a semiactive image-guided system to manufacture a template was described. Further, a 4-DOF robot was developed to verify error of drilling that resulted in a maximum translation of only 0.2 mm with 1.1° in rotation. Chiarelli and colleagues[12] also evaluated the accuracy of surgical templates based on image data with a noninvasive radiological stent transfer. When performing a surgical procedure by robot, the precision achieved was suitable for clinical needs (0.283 mm $\pm$ 0.073 mm average position error and 1.798° $\pm$ 0.496° average orientation error), which is better than stents based on stereolithography. Robot-assisted manufacture of surgical templates can fully guide implant trajectory, be less expensive, and be minimally invasive. In addition, with less accurate tissue-supported surgical guides commonly in use, there is a great need for human error to be curtailed in clinical practice.

ROBOT-ASSISTED DENTAL IMPLANTOLOGY

The accuracy of implant placement is among the most important factors that influences the outcome of implant therapy and associated rehabilitation. Surgical navigation systems and template guidance meet the demands of high accuracy of implant placement and positioning. Surgeons have tried to use this technique to reduce errors of implant positioning. However, the physical position of a surgeon is often constrained due to the limitation of a patient's mouth opening and the location of missing teeth. Because of this, the surgeon's performance may be affected by stamina and fatigue, and the possibility of human error cannot be eliminated. Therefore, robotic surgery has the advantage of sustained precision, increased stability, greater efficiency, and more flexibility for assisting dental implant preparation and implantation. This is a remarkable statement to make at a time when only a handful of clinicians have used the technology worldwide.

The first study of robot-assisted dental implantation to minimize error was presented by Boesecke and colleagues (Medical Intelligence, Schwabmünchen, Germany) in 2002.[13] This robot system had a working area scope of 700 mm and was used to assist a surgeon during implant osteotomy site preparation by holding a drilling guide. They reported findings on 48 implant placements, including deviation at the entry site, which were observed to be within 1 to 2 mm in the apical region. Ten years later, an automated robotic dental implantation system with 6 DOF was presented that could mill a natural root-shape implant in the jaw model by using a volume-decomposition–based program.[14] Later, a 3-DOF robot with stereo camera was released that was capable of detecting and modulating the handpiece to ensure the implant was positioned according to preoperative planning.[15] The manipulator automatically applied information for where to start cutting and automatically adjusted the force applied accordingly.

In 2017, the world's first commercial dental robotic system, YOMI (Neosis, Miami, FL, USA), was developed and received FDA clearance.[16] The guidance system, termed haptic robotic technology, directed surgeons during drilling based on the desired preoperative trajectory. YOMI delivers physical guidance by constraining the drill position, orientation, and depth, thereby alleviating the need to prepare a custom surgical guide and simultaneously preventing deviation of the surgeon's hand. This technology provides extremely high accuracy and predictability during preparation of an implant osteotomy via receipt of vibrational feedback. However, YOMI should be used under supervision and is relatively expensive to purchase.

At the end of 2017, the world's first autonomous dental implant placement system was introduced by Zhao.[17] This intelligent robot has a high degree of autonomy, can automatically adjust continuously during intraoperative procedures, and can execute surgical tasks directly on patients without any apparent control by a surgeon. However, limited confirming research is available regarding the reliability and feasibility of this system in clinical practice. Much more research is necessary to evaluate inaccuracy and implant positioning to validate robot intelligence–generated procedures.

The main components of surgical robotics involve 2 elements (**Fig. 1**): an image guidance system and a motile robotic system. Image guidance software allows for preoperative planning relative to the surgical site, and a prosthesis can be simulated from the software model or by merging with a mockup image or Stereolithography format. At this point, the 3-dimensional denture data can be transmitted to the robot system.[18]

Registration is foundational to navigation and surgical robotics determination of the spatial relationship. Robots must be aware of 3 coordinate frames in the X, Y, and Z axes as the preoperative plan and the anatomic object are addressed within in the robot's workspace. The degree of accuracy of the registration procedure can be assessed by the degree of correlation between image information in the system and the preoperative plan. Different methods of registration have been discussed and have been shown to significantly influence accuracy the surgical outcome. The bone-anchorage fiducial is considered the gold standard due to its rigid attachment and clear CT image contrasting the registration template and anatomic landmarks. The coordinate measurement machine (CMM) was introduced as a reference coordinate system to help set coordinate points between the robot and the surgical field.[14,19]

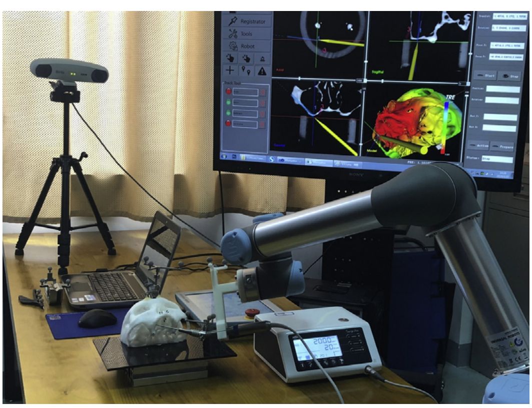

Fig. 1. The surgical robotic system includes the following elements: robot arm, surgical navigation system, optical tracking device, and preoperative planning software.

A registration was first performed by surgeon and the robot using a 2-step procedure. First, the surgeon recorded the fiducial configuration on the jaw model to transfer virtual coordinates to reference coordinates by using CMM. Second, registration between the reference coordinate and the surgical tool coordinates were assessed using another fiducial configuration. Final target registration error after this 2-step registration process was 1.42 plus or minus 0.70 mm.[19]

The accuracy is quite good but a few concerns with this system have been described.[12] The system depends significantly on a third-party software and relevant anatomies are not fundamentally measured during planning. Furthermore, a patient needs to keep still during the operation. When there is patient discomfort, subsequent movement predisposes to error during registration.

Robots are generally defined as computer-controlled devices with 5 or 6 DOF that can execute complex movements with high accuracy. Different types of medical robots have been tested in dental implantology. Telemanipulated robots are nonautonomous master-slave robots controlled by a surgeon using a force-feedback haptic device.[20] Amjad and colleagues[21] presented this type of robot with virtual force feedback and an image-guided system. The system is composed of 4 major parts: a preoperative surgical planning system, a virtual force feedback haptic, a 6-DOF manipulator, and an image-guided navigation system. Haptic devices have become an essential part of telerobotic surgery, as have surgical simulation systems that minimize the risk of bone perforation and soft tissue injury. However, the accuracy of telerobots depends highly on the surgeon's experience. Xiaojun and colleagues[22] presented a model of teaching telerobots to train unexperienced surgeons and students. With integrated surgical planning and a virtual training system, surgeons could learn to identify the sense of different tissue boundaries and the appropriate amount of force to prepare the implant bed. Yu and colleagues[15,23–27] have carried out a series of investigations into telerobotic-assisted drilling systems. The use of algorithm-based modulated potential field is extended to use with a 5-DOF robot manipulator for position adjustment and angle adjustment to locate the entry point and implant trajectory.[24] Then, a stereo camera helps to detect the relative position from the end effector (handpiece) to the target.[15,25] The surgeon-manipulator automatically adjusts the force when it approaches the endpoint of the osteotomy. The relationship between cutting force and torque and CT value was also evaluated.[26,27] In summary, this type of robot can achieve automatic force adjustment by estimating the patient's CT value in real time. Although a modulated potential field guides trajectory of drilling, it does not provide information regarding insertion torque and force feedback, which are important for use in immediate function implantology.

Remarkable progress has been achieved in automatic robotic systems. In 2017, the world's first autonomous dental implant robot was developed by Beijing University (Beijing, China) and the Fourth Military Medical University Hospital (Xi'an, China). The robot aim was to avoid human surgical error, as well as address a shortage of qualified dentists in China.[17] The system is made up of an image-guided platform, a commercial mechanical robot, an implantation platform, and DentalNavi software (The fourth military medical university, Sichuan, china). Four types of dentition defect models with spatial mapping devices are used to locate a patient's coordinates, and to calibrate with the operation platform, the robot system, and the image-guided system. After implant placement into models, postoperative cone beam CT was merged with the desired preoperative trajectory and the accuracy was evaluated. The result showed the mean entry deviations to be 0.705 mm plus or minus 0.145 mm, the mean apical deviation to be 0.998 mm plus or minus 0.232 mm, and the mean axis deviation to be 2.077 plus or minus 0.455°,[28] which is a remarkable achievement.

Another surgical automatic robotic system was later evaluated with regard to the accuracy of zygomatic implant placement in the edentulous maxilla. In this in vitro study, the investigators demonstrated that long implants (50 mm), such as zygomatic implants, may also be placed accurately[29] (Fig. 2).

Fig. 2. A surgical automatic robotic for zygomatic implant placement has been tested in a 3-dimensional printed model.

SUMMARY

Early experience with robotic dental implant surgery accuracy for the use in implant osteotomy preparation is beginning to gain traction with only a few clinical studies at present. Robotic osteotomy deviations of less than 1 mm and angle deviations 2° or less suggest the technology holds significant promise. However, capable robotic application for determining implant insertion torque is still not available. Despite limitations and early development difficulties, the future of robotic use in this field seems certain to flourish as systems improve and costs go down.

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