Robotic Otology

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17.1 Introduction

Otologic surgery is an attractive otolaryngologic field for the implementation of robotic systems as a means to improve surgical outcome. In particular, given the physical millimetric restrictions in surgical access to inner ear sites and the microscopic anatomical elements within the middle ear space, surgical precision is of paramount importance during these cases.

The introduction of the otologic microscope to the field during the 1950s led to a revolution in otologic surgery [1], effectively making a myriad of previously unthinkable surgical maneuvers physically possible. The breakthrough of microscopic visualization coupled with the use of the high powered dental-type burrs, along with continuous suction and irrigation in place of the mallet, gouge, and rongeur forceps, gave rise to a whole new field of surgical hearing restoration. Examples include different tympanoplasty and stapes surgical techniques, mastoidectomy with safe facial recess drilling, cochleostomy, labyrinthectomy, and improved cholesteatoma extirpation, just to name a few. More recently, endoscopic otologic surgery has become a popular and burgeoning alternative to traditional binocular microscopic approaches [2]. Many advantages relative to the microscope are reported. For one, there is a dramatically improved field of view with comparable or improved magnification of the middle ear space. The endoscopes allow for visualization "around corners," clefts, and recesses. No longer are areas of the middle ear "hidden" from view. In fact, a whole realm of middle ear anatomy is being defined due to the improvement in optics conferred by the endoscope [3]. Regardless of microscopic or endoscopic visualization, precision in terms of optics and magnification are crucial factors for otologic surgery.

A second aspect of otologic surgery, attractive for robotic applications, is that the anatomical components of the ear, housed within the confines of the temporal bone, are fixed in bone and as such are highly predictable and stable in terms of the limits of their location and limits of dissection. With increasing resolution of temporal bone imaging ostensibly resulting in improved segmentation of middle ear structures, it is becoming increasingly feasible to preprogram the location and physical extent of critical landmarks into complete or partial automation systems for otologic surgery, including robotics. As an example, for cochlear implantation (CI), there are critical structures that need to be avoided, and an accurate path has to be opened through the bone to expose and enter

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the cochlea at a specific and precise location, relative to the round window. Appropriate cochleostomy placement is critical to allow for scala tympani cochlear electrode array insertion. Recent studies, however, suggest that a significant proportion of cochlear implant surgeons do not adequately position the cochleostomy anterior inferior to the round window, into the scala tympani [4, 5]. Arguably, this is attributed to the fact that less experienced surgeons are more likely to have inadequate exposure of the round window through the facial recess. This is in part likely due to a fear of injuring the facial nerve, causing some to leave the bone overlying the nerve undrilled, incompletely opening the facial recess and obscuring the round window view. Other potential factors that contribute to an inadequate cochleostomy placement include variable round window anatomy, a poor angle of visualization approach, and a lack of understanding of cochlear anatomy. These factors are especially prevalent in cases involving very young or otitis-prone children with poorly pneumatized mastoids, in complicated revision cases, or in cases with complex or absent bony landmarks. Indeed, increasingly precise surgical robotic systems capable of providing either immediate intraoperative feedback of temporal bone anatomy or further automating temporal bone surgery could potentially be revolutionary. This is true not only in cochlear implantation but in other otologic procedures, such as those requiring hearing preservation to remove cerebellopontine angle tumors, petrous apex approaches, and labyrinthectomy.

Despite these attractive characteristics for the usage of robotic systems in otologic surgery, as of yet no such system has been implemented for widespread clinical use. Perhaps the most amount of progress has been made in the development of a fully automated CI robot, but clinical acceptance and implementation remains to be seen. This chapter will review work done in the field of otologic robotic surgery and articulate advantages of these efforts along with potential current limitations or roadblocks to widespread surgical utilization.

17.2 Definitions

17.2.1 Robot

The term “robot” was coined by the Czech playright Karel Capek in 1921 [6]. The word “robot” is from the Czech word “robota” which means forced labor [6]. Since that time, robots have developed for a variety of applications such as manufacturing, surgery, rehabilitation, aerospace functions, home service, military purposes, rescue missions, inspection, sports, and entertainment.

17.2.2 DOF

An object has n degrees of freedom (DOF) if its configuration can be minimally specified by n parameters [7]. A rigid body in three-dimensional space would normally have six DOFs, three translational (up and down, left and right, forward and backward) and three rotational (roll, yaw, and pitch). A human arm has seven controllable DOFs in total; three DOF are provided by the shoulder, one by the elbow, and three by the wrist [6].

17.3 History of Robotics Including Medical Robotics

The first application of robot in the surgery field was in a neurosurgical procedure in 1985 [8]. This robot was named the PUMA 560 and applied to improve the position accuracy of a needle for the computerized tomography (CT)-guided brain tumor biopsies. However, its use was stopped because of specific safety issues. Three years later, using the same machine at the Imperial College in England, a transurethral resection of the prostate was performed [9]. This system was called the PROBOT and became the first self-navigated, robotic-based surgical procedure. The navigational plan consisted of a three-dimensional model of the prostate, and the determination of the resection area by the surgeon. Using this plan, the calculation of the cutting trajectories and execution of the procedure was carried out by the robot. A few years later in 1992, the ROBODOC was developed by International Business Machines (IBM, New York, USA) Corporation and associates to help surgeons to mill out precision prosthetic fittings in the femur for total hip replacement [10]. This became the first robot approved by the Food and Drug Administration (FDA) for medical use. Simultaneously, robotic telepresence or telesurgery technology was developed at the Stanford Research Institute (SRI), National Aeronautics and Space Administration (NASA), and the Department of Defense (DOD) [11]. These efforts developed the technologies for surgeons to remotely perform procedures at a distance from the operating room, with target applications such as immediate operative care in the battlefield. The commercialization of immersive telepresence for robotic medical laparoscopy (where a surgeon can operate across the room from a patient by directing robotic arms via controls and a video display) was achieved with the da Vinci Surgical System (Intuitive Surgical Inc., Sunnyvale, CA), [12]. It received FDA approval in 2000 as the first comprehensive robotic system for laparoscopic surgery. Aside from a vision console, this robotic system consists of a surgeon-side console (master), controlled by a surgeon, and a patient-side console (slave), a robotic module consisting of three or four arms, one for holding the laparoscope and rest of the arms for surgical instruments. These instruments are inserted into the patient through ports similar to those used for laparoscopic/endoscopic surgery. The arms of the slave console follow the commands received from input manipulators on the surgeon-side console (Fig. 17.1 from [13]).

Using this system, tremor filtering, movement scaling, increased range of motion, and improved ergonomics could be achieved. The input manipulators allow for seven DOFs, i.e., the surgeon

Fig. 17.1 Da Vinci Surgical System 2010 Intuitive Surgical, Inc. (With permission) [13]

can roll; pitch; yaw; move in x, y, z direction; and grip using the laparoscopic tools. The imaging system provides the surgeon with a high-definition, 3D magnified image of the operative field with the use of two independent cameras in the dual-channel endoscopes [6].

Around the same time of the introduction of the da Vinci robot, Computer Motion (merged with Intuitive Surgical Inc. in 2003) revealed the AESOP (Automated Endoscopic System for Optimal Positioning) as the first laparoscopic camera holder, while voice activation was added later [12]. After that, Computer Motion produced an integrated robotic system termed the ZEUS surgical system [11, 12]. ZEUS has three robotic arms that are mounted on the operating table [14]. One robotic arm is AESOP, which helps the surgeon with a better vision from inside the patient's body. The other two arms of ZEUS are the extension of the left and right arms of the surgeon to support precise incisions and extractions. Similar to the da Vinci system, surgeons sit at a console and wear special glasses to see a three-dimensional image. However, ZEUS differs from the da Vinci system because its AESOP part can respond to voice commands. The FDA cleared AESOP and ZEUS in 1994 and 2001, respectively.

Historically, robotic have contributed to and impacted surgery areas such as neurosurgery, orthopedics, maxillofacial, ophthalmology, urology, gastrointestinal surgery, and cardiac surgery [12]. The da Vinci robot has been used in many different procedures such as cardiothoracic surgery, general surgery, gynecology, and urology [15]. For example, in glottis cancer, the adaptation of laser cutters to the suite of da Vinci robotic instruments has made a robotic approach practical [16]. What's more, the design of flexible robots advances robotic surgery further by addressing the limitations related to rigid endoscopy [16]. Recently, intraoperative image-based techniques have also been shown to help surgeons to more accurately localize and to reach desired structures without violating neighboring critical structures [17–19].

17.4 Advantages and Disadvantages of Robotics in the Medical Field

Compared to conventional open surgery, robots have been purported to provide many advantages. A list of these advantages, paramount in otologic surgery, is summarized below [6]:

1. Increased accuracy and surgical precision
2. Improved three-dimensional visualization and magnification relative to binocular microscopy
3. Less invasive access with the potential for minimizing recovery time and downstream surgical costs
4. Improved stability through scaling of surgical maneuvers
5. Improved ergonomics for the surgeon
6. Better access due to afforded higher degree of freedom
7. Articulation beyond normal manipulation
8. Ability to perform operations from a distance (telesurgery)

In spite of the main advantages acquired by a surgical robot, some limitations have been reported as well [6]:

1. High initial and subsequent maintenance costs
2. Need to train surgeon and staffs
3. Prolonged learning curve
4. Lack of haptic feedback to the operator
5. Need to get FDA approval, which is expensive and time consuming

17.5 Robotics in Otologic Surgery

Robotic systems in otologic surgery can be categorized in three classes: (1) telerobotic, (2) cooperative, and (3) autonomous robotic system. Each category is described below.

Previous efforts incorporating robotics into otologic surgery are summarized in Table 17.1 and will be further discussed below.

17.5.1 Telerobotic Systems

This type of robotic system consists of a master and a slave component with a surgeon included in the control loop. In other words, the surgeon uses a master robot or a joystick to send commands to the slave robot to perform a task on a patient. Telerobotic systems consist of two different types: (1) unilateral telerobotic system and (2) bilateral telerobotic systems. Unilateral telerobotic system does not provide force feedback on the master side, while bilateral telerobotic systems provide force feedback on the master side. For example, the da Vinci robot is a unilateral telerobotic system. Otologic surgery is exceedingly delicate as Nguyen et al. [20] showed that a 5 μm positional resolution and an angular resolution of 0.3° are required. This degree of accuracy is quite difficult to achieve for even the most skilled surgeon. However, a telerobotic system which supports position scaling could possibly make this level of accuracy more universally attainable. Improved visualization within the middle ear could also be achieved by powerful high-definition endoscopic systems, held distally in the surgical field, thus preserving the field of vision.

Table 17.1 Summary of reported robotic system studies in otologic surgery

Author name and year of publication	Type of robot	Study type	Clinical application	Figure number
Nguyen et al. [20] (2011)	Telerobotic system 6 DOF	Phantom	Stapedectomy	2
Liu et al. [21] (2014)	Telerobotic system 7 DOF	Cadaveric ($^{*}N = 1$)	Cochlear implant	3
ROTHBAUM et al. [23] (2002)	Cooperative robotic system 6 DOF	Phantom	Stapedectomy	4
Majdani et al. [27] (2009)	Autonomous robotic system	Phantom	Cochlear implant electrode insertion	5
Schurzig et al. [26] (2010)	1 DOF			
Bell et al. [17] (2012)	Autonomous robotic system 5 DOF	Cadaveric ($N = 15$)	Cochlear electrode insertion	6
Dillon et al. [18] (2014)	Autonomous robotic system 4 DOF	Phantom	Temporal bone milling	7
Danilchenko et al. [19] (2011)	Autonomous robotic system 6 DOF	Cadaveric ($N = 3$)	Mastoidectomy	8

$^{*}N$ Number of studies

17.5.1.1 Examples in Otologic Surgery

- *RobOtol* [20]: Nguyen et al. developed a telerobotic system including a master robot and a slave robot. The slave robot's kinematic chain was composed of three perpendicular linear links at the base and three rotary links at the distal part of the arm, as shown in Fig. 17.2. During otologic surgery, the field of view is quite limited. The vision axis and the approach are almost collinear. The tools have to be very thin and are held far from the tip to avoid blocking of the target. To reduce the visual impairment, a cable transmission mechanism was used to allow for the placement of the two last actuators at the base of the robot arm. The master robot consists of the surgeon controlling the arm remotely using by a pen-like interface with six degrees of freedom (Phantom Omni, Sensable Technologies, Inc., Woburn, MA). Otosclerosis surgery was considered as a model to define the specifications of this robot for a tele-operated otologic surgery. The prototype was tested in human temporal bone specimens by otologists. Duration of procedure, distance covered by the tool, and the number of times the emergency button was pressed were three measures that were considered during the evaluation of the system performance in both position mode and velocity control mode. The operator was able to reach all four target points on the tympanic membrane, the stapes footplate, and the round window in all three temporal bones in velocity command mode. Incus-stapes disjunction and stapes removal were performed successfully under the microscope and with the endoscope in two temporal bones. All participants were able to complete placement of the piston prosthesis in the stapedotomy in both velocity-to-position and position-to-position command modes.
- *Modified tool for the da Vinci robot* [21]: Liu et al. reported on a cadaveric feasibility study of usage of the da Vinci system for cochlear implantation. For this purpose, the group developed an attachment which allowed for a pneumatic-powered drill to be coupled to one of the working arms of the da Vinci robot, as shown in Fig. 17.3. For this study, integration of augmented reality through segmentation of

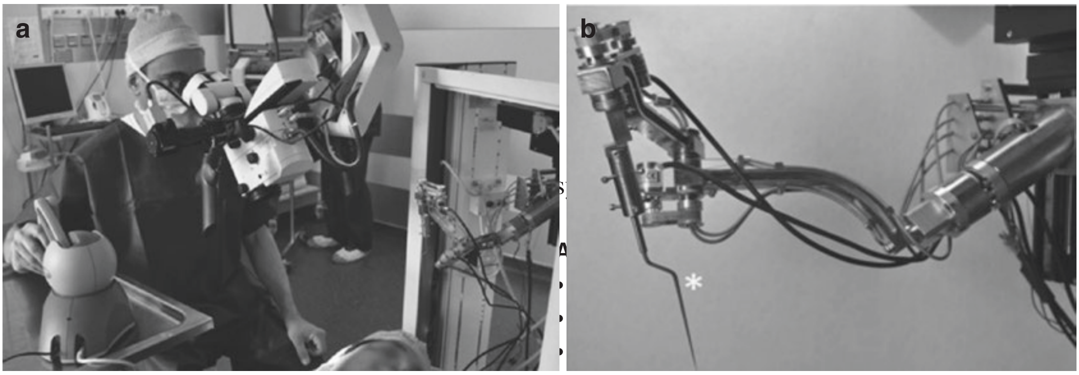

Fig. 17.2 Telerobotic system. (**a**) Phantom Omni interface (Master robot), (**b**) the RobOtol prototype (Slave robot) [20]

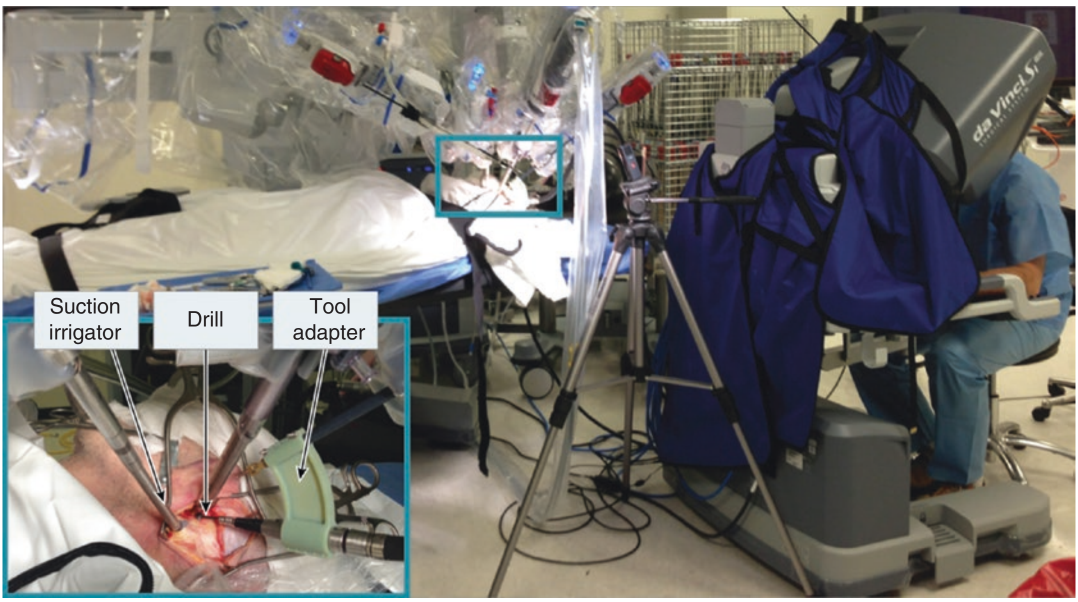

Fig. 17.3 Operating room with the da Vinci Si for otologic surgery. *Inset* is a close-up of the initial position of the endoscope, suction/irrigator, and drill attached with the custom tool adapter (With permission) [21]

implementation. First, the magnification of the robotic 3D endoscope for improved visualization through the posterior tympanostomy was felt to be noticeably inferior. Second, the study reported that the existing robotic arm surgical tools, such as the suction irrigator, were found to be too large for dissection through the posterior tympanostomy approach to the cochlea. However, though the lack of haptic feedback is an undesired effect, it was

- Comfortable pose for surgeon
- Safety enforcement using forbidden zone concept (virtual fixture)
- Improved dexterity in limited space because of small slave robots
- Better line of sight

Disadvantages

- Limited perception of contact by surgeon for unilateral telerobotic system

- Possibility of instability highlighting the requirement for more robust control system for bilateral telerobotic system
- Lack of haptic feedback in currently available commercial systems such as the da Vinci.
- Longer procedure time with currently available systems

17.5.2 Cooperative Robotic System

Cooperative robotic system are designed to extend human performance to permit fine manipulation tasks that are normally considered difficult or impossible and allow for even less experienced surgeons achieve higher performance outcomes. In this type of robotic system, the surgeon and the robot cooperate to perform a task. Robotics are therefore incorporated to allow surgeons to overcome to human natural physical limitations in both dexterity (tremor, jerk, drift, and overshoot) and tactile sensitivity [22, 23].

According to the Committee on Hearing and Equilibrium, primary stapedotomy has a reported success rate of approximately 70 %. Complications associated with stapedotomy typically result from either cochlear or labyrinthine trauma. As manifested by decreases in pure tone thresholds and speech discrimination scores, cochlear trauma leads to sensorineural hearing loss in 5–15 % of patients. Vertigo occurs in approximately 2 % of patients. For stapedotomy, surgical skill is among the most important variables predicting outcome. In fact, it has been postulated that given a wide large learning curve for this surgical procedure, only surgeons with significant experience should perform the operation [24, 25].

17.5.2.1 Examples in Otologic Surgery

- *Steady-hand (SH) robot* [23]: In the SH robotic system, the operator shares the control of surgical tool with a robot arm, as illustrated in Fig. 17.4. The surgeon and robot co-manipulate the surgical tool. The robot senses the forces exerted by the surgeon on the handle as well as the tool-tip forces and synthesizes this information to provide tremor-free positional control. The SH robot dampens high-frequency movement (i.e., tremor) like a viscous system. While using the SH robot, the surgeon has reported to feel like he/she is manipulating the surgical tool in a “viscous fluid.” For certain tasks, the SH robot has been shown to enhance dexterity.

Rothbaum et al. performed experimental studies using SH robot and a surgical model of stapedotomy based on a human temporal bone, to show the effect of force feedback provided by cooperative robots on five fenestrations under three different experimental conditions: (1) free hand (FH), that is, no robotic assistance, (2) robotic assistance with 1:1 force feedback (force-feedback mode), and (3) robotic assistance with 2:1 force scaling (force-scaling mode). For evaluating the efficacy of SH robot, stapedotomy performance was investigated and compared for (1) manual and (2) with robotic assistance. Furthermore, to evaluate subspecialty expert/novice differences, the performance of micropick fenestration of the stapes footplate was studied. The SH robot significantly (approximately 58 %) reduced the cumulative force applied to the stapes footplate in the force-feedback mode. Cumulative force was not significantly affected by surgeon experience. Neither surgeon experience nor SH robotic assistance affected maximum force or fenestration targeting (displacement) in force-feedback mode. Both cumulative force and duration of fenestration were significantly reduced by SH

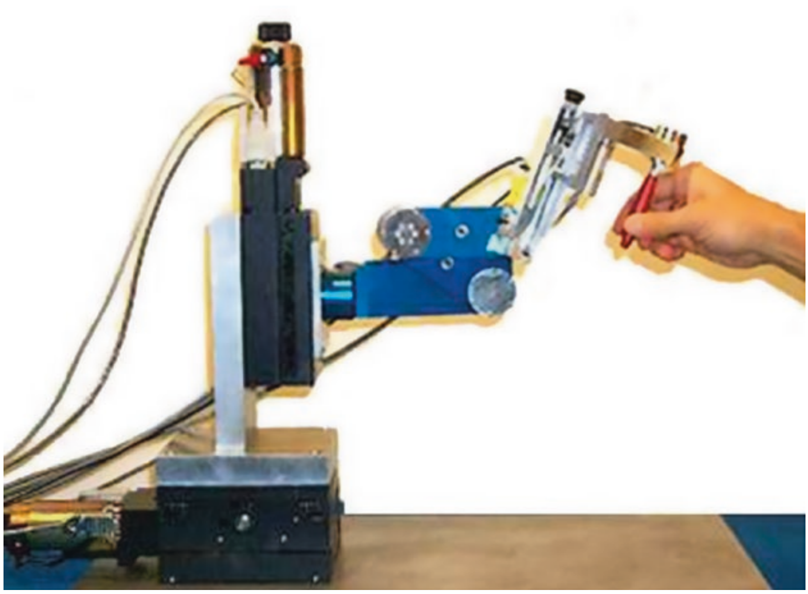

Fig. 17.4 The Johns Hopkins University steady-hand robot for cooperative human-machine microsurgical manipulation [22]

robot assistance in force feedback. Tremor reduction significantly affected two performance variables: (1) cumulative force applied to the stapes footplate and (2) fenestration targeting. The reductions in the duration of fenestration caused reduction in cumulative force. According to Rothman et al., the mechanism by which tremor reduction decreases duration of fenestration is uncertain; perhaps the steadying nature of the system could make operators more confident in the precise movements of fenestration.

Advantages and disadvantages of cooperative robotic system for ear surgery are listed next.

Advantages

- Surgeon's hand tremor elimination.
- Safety enforcement using forbidden zone concept (virtual fixture).
- More precise motions.
- Force feedback and force-scaling may be integrated.

Disadvantages

- May limit dexterity of the surgeon.
- Robot may obstruct the surgeon's line of sight and requires that the surgeon modify the angle of approach to the footplate.
- Longer procedure time.

17.5.3 Autonomous Robotic System

In an autonomous robotic system, the robot itself can perform part of or the entire task. In ear surgery, this kind of robot usually requires preoperative imaging, such as MRI or CT data, to perform path planning. In the field of otology, a main task of otological cases is the mastoidectomy, in which bone is milled away while exposing but not damaging vital anatomy. Mastoidectomy could be a good fit for an autonomous robotic approach since: (a) the tissue to be resected is encased in rigid bone, and (b) critical anatomical features remain hidden until they are revealed by ablation. The first of these two reasons makes surgery with the autonomous robot feasible; the second makes it useful since less intracochlear trauma would occur especially considering that the rupture force of the basilar member in a human cadaver is 0.029–0.039 N [26]. The robot, guided by images that see beneath the surface, can safely ablate bone to which the human operator would be blind.

The rigidity of bone is essential because it ensures that the three-dimensional structure of the target anatomy remains the same during preoperative imaging/planning and during subsequent intervention.

17.5.3.1 Examples in Otologic Surgery

- *A.K. A robot* [26, 27]: Labadie et al. applied an automatic robotic cochlear implant insertion tool with the Advanced Off-Stylet (AOS) technique, in which the stylet and electrode array are withdrawn simultaneously, to insert the electrode array into an anatomically correct, three-dimensional scala tympani model (Med-el Corporation; Innsbruck, Austria). The main advantage of AOS technique is the decreased likelihood of intracochlear damage by restricting the physical contact between the electrode array and the lateral wall of the cochlea. The robot had one degree of freedom and used two independent piezoelectric step motors with positional accuracy of 1 μm and maximum velocity of 5 mm/s (SmarAct GmbH; Oldenburg, Germany). The electrode array was grasped by a modified surgical alligator forceps, and stylet was held via a stainless steel hooked wire. During the insertion, the force resulting from the contact between the electrode array and scala tympani model was measured by four semiconductor strain gauges (model SS-060-033-1000 PB; Micron Instruments, Inc.; Simi Valley, CA) coupled to the insertion tool. In Fig. 17.5, the experimental setup using a scala tympani model is shown. The insertion force generated by this technique was compared with the human operators and the robotic insertion tool via the traditional technique, in which the stylet is removed after complete insertion of the electrode, respectively in [26, 27]. Compared to human operators, the robot achieved more repeatable results, fewer relative force peaks, and slightly higher average force values, may not be clinically significant. Additionally, beyond 7 mm insertion depth, cochlear implant electrode insertion via AOS could reach to a significant reduction in both average and maximal force in comparison with the traditional insertion technique.
- *Bone-attached robotic system* [17, 18]: The robotic system developed in [17], shown in Fig. 17.6, was specifically designed for lateral skull-based surgery. It consists of a table-mounted robotic arm (Fisso, Baitella AG, Switzerland), a force-torque sensor (Mini40, ATI, USA) for moving the tool tip to any desired position by a surgeon, an optical tracking system for verifying the tool position, an image-guidance system for preoperative and postoperative analysis, head fixation system (FixIT, Medicon Medical Instruments, Germany), and a touch screen interface for controlling the robot actions and status. Compared to the existing approaches based on industrial robots, this robot showed equal or better accuracy levels with a better compatibility with a clinical environment because of its overall weight (5.5 kg) and size (total arm length = 65 cm). However, this design was dependent on a tracking system and the error related to the monitoring and alignment of the patient with the robot. To eliminate the mentioned limitation, Dillon et al. proposed a compact and bone-attached robot with a preoperative CT scan-based plan for temporal bone milling [18]. The robot in discussion, illustrated in Fig. 17.7, a four-axis milling

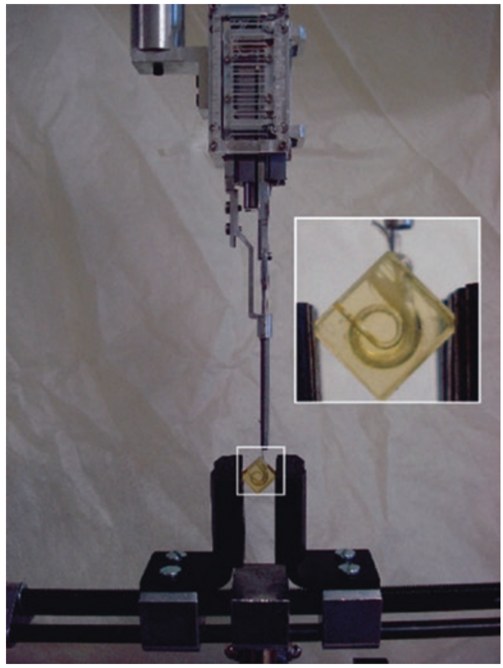

Fig. 17.5 Experimental setup of electrode insertion above the scala tympani model [26]

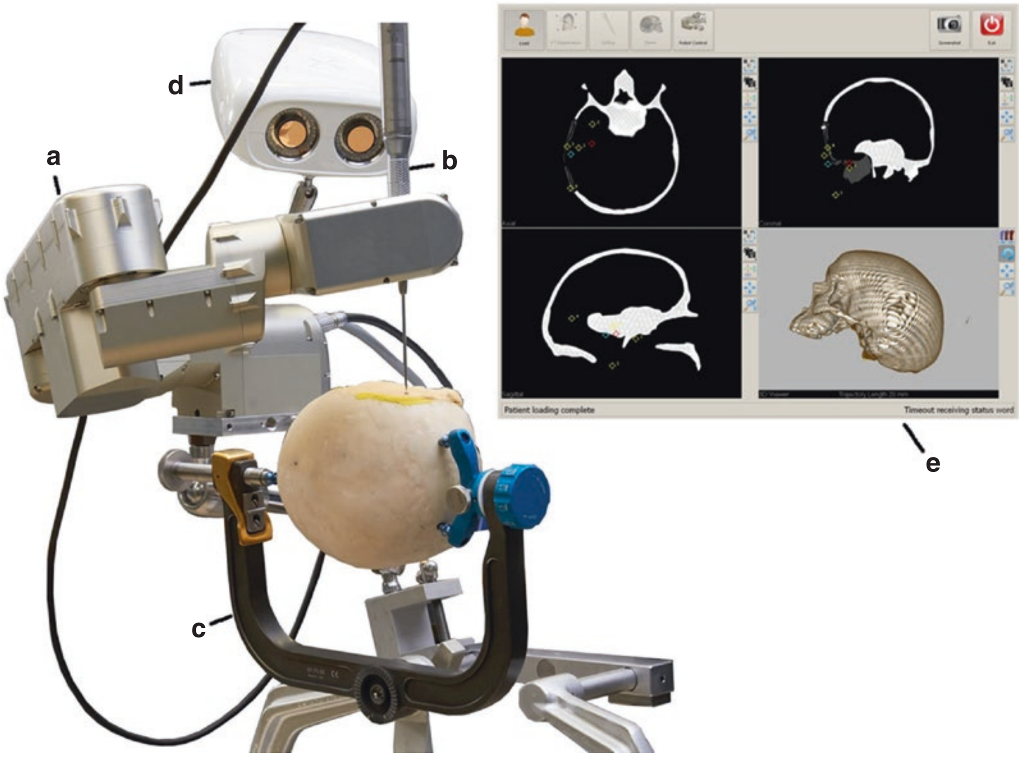

Fig. 17.6 Overview of the robot navigation system. (**a**) The mounted robot to the OR table, (**b**) a conventional surgical drill, (**c**) a head clamp, (**d**) an optical tracking system, and (**e**) a touch screen interface [17]

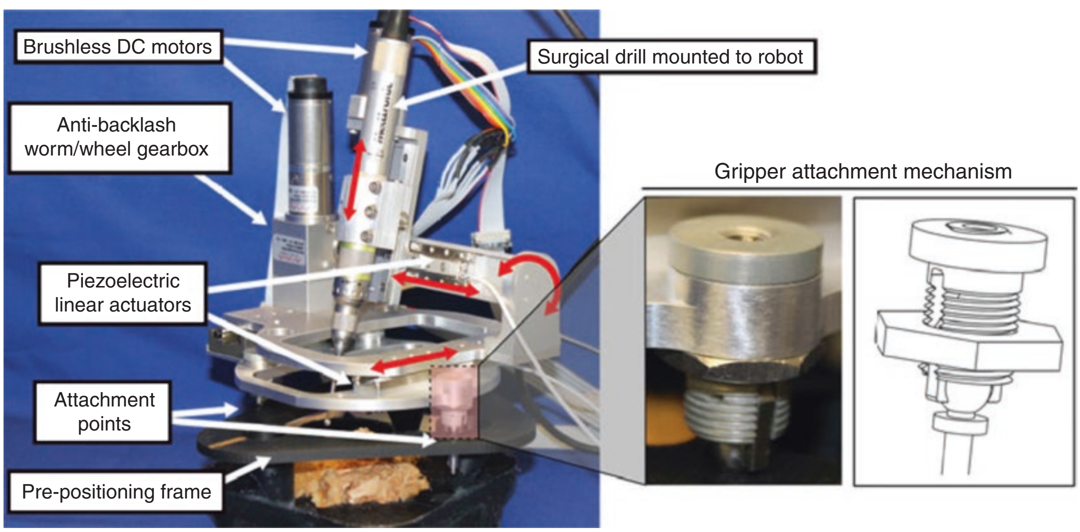

Fig. 17.7 Compact and bone-attached robot with test sample attached the prepositioning frame (PPF) using spherical gripper mechanisms [18]

machine, consists of piezoelectric linear actuators (SmarAct GmbH, Oldenburg, Germany) for moving along the x- and y-directions, a brushless DC motor (Maxon Precision Motor, Inc., Fall River, MA, USA) with a lead screw for moving along the z-direction, and a brushless DC motor and anti-backlash worm-wheel gearbox (Gysin AG, Itingen, Switzerland) for rotating about the x-direction. Moreover, the robot was attached to the patient via three titanium spheres on a prepositioning frame (PPF). Preoperative planning for the robot trajectory incorporated cutting velocity and drill angle considerations, which was determined through the segmentation of critical structures and target volume from CT images registered to the patient by the three spheres in the PPF. The trial results on a phantom showed that the proposed robotic system was accurate and the experimentally removed volume did not overlap with the critical structures.

- *OTOBOT* [19]: Danilchenko et al. reported the first usage of an autonomous robot for percutaneous placement of a cochlear implant in a cadaveric model using infrared tracking to monitor the motion of both the specimen and the robot. In their work, a developed version of the OTOBOT system was used, which incorporates a Mitsubishi RV-3S industrial robot (Mitsubishi Electric & Electronics USA, Inc., Cyprus, CA) controlled by custom software. Also, bone-implanted markers were applied to register the physical space to CT image space, in which the boundaries of the regions to be milled were specified. In Fig. 17.8, the configuration of the developed system is presented. Based on the acquired results, the proposed system is accurate and reliable, but its performance is dependent on the registration accuracy level.

Advantages and disadvantages of autonomous robotic systems for ear surgery are listed next.

Advantages

- The target volume to be removed is manually identified by the surgeon preoperatively.
- Consistent outcome independent of the surgeon.
- Preplanning to avoid facial nerves and veins.
- May result in shorter time of procedure.

Disadvantages

- Risk of damage to critical structures if preplanning is not accurate enough.
- Setup time may prolong the procedure time.
- Possible requirement for multiple CT scans with attendant radiation exposure, i.e., both the preoperative and intraoperative CT scan.
- Necessity for surgeons and patients to take a "leap of faith" in terms of allowing a robot to complete the surgery from beginning to end.

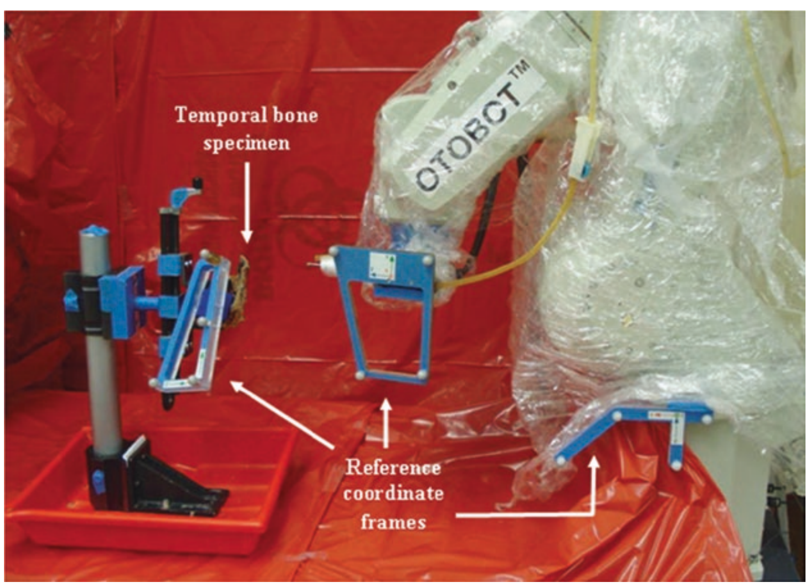

Fig. 17.8 Setup of the OTOBOT robotic system to perform mastoidectomy on patient [19]

Conclusion

Otologic surgery combines difficulties of microsurgery and endoscopic surgery. This surgery is performed on fragile millimetric structures. Therefore, precise control of movement and forces under microscopic magnification (up to 40 times) is a necessity. In addition, many tasks are performed through a keyhole approach represented by the external auditory canal. Thus, to maximize the field of vision, appropriate instruments should be thin and long. Therefore, endoscopes are less likely to be employed in ear surgery due to their large diameters and the risk of trauma to the ossicular chain during placement in the tympanic cavity. While several characteristics of the da Vinci Surgical System (e.g., remote center of motion, near-field 3D vision) may be important in the otologic surgery, the current overall dimensions of the da Vinci robot, especially the distal diameter of its tools (5 mm), seem to be too large for otologic surgery.

The researched robotic systems in otologic surgery could be categorized in three classes, including (1) telerobotic system, (2) cooperative robotic system, and (3) autonomous robotic system. As described in the previous subsections, each of these categorized robotic systems has distinct advantages and disadvantages. Since there are complex anatomy and presence of many critical structures embedded within the bone area, we believe that the latter approach, i.e., image-guided autonomous robotic intervention, is well suited for inner ear surgery compared to the others. While some phantom and cadaveric studies have been reported in the literature of this field, based on the information summarized in Table 17.1, and to the best of our knowledge, there is no reported clinical study using autonomous robotic systems in otologic surgery so far.

As a future work, in order to make the robotic-assisted otologic surgery clinically practical, the following issues should be addressed.

1. Reduction in the robotic instrument size
2. Improving the path planning and trajectory planning
3. Improving patient safety features
4. Improving the tactile and haptic perception during surgery
5. Minimal change in the surgical workflow in order to switch ability to the manual procedures in the case of complication

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