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Review

Robotic Systems for Cochlear Implant Surgeries: A Review of Robotic Design and Clinical Outcomes

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Abstract

Sensorineural hearing loss occurs when cochlear hair cells fail to convert mechanical sound waves into electrical signals transmitted via the auditory nerve. Cochlear implants (CIs) restore hearing by directly stimulating the auditory nerve with electrical impulses, often while preserving residual hearing. Over the past two decades, robotic-assisted techniques in otologic surgery have gained prominence for improving precision and safety. Robotic systems support critical procedures such as mastoidectomy, cochleostomy drilling, and electrode array (EA) insertion. These technologies aim to minimize trauma and enhance hearing preservation. Despite the outpatient nature of most CI surgeries, surgeons still face challenges, including anatomical complexity, imaging demands, and rising costs. Robotic systems help address these issues by streamlining workflows, reducing variability, and improving electrode placement accuracy. This review evaluates robotic systems developed for cochlear implantation, focusing on their design, surgical integration, and clinical outcomes. This review concludes that robotic systems offer low insertion speed, which leads to reduced insertion forces and lower intracochlear pressure. However, their impact on trauma, long-term hearing preservation, and speech outcome remains uncertain. Further research is needed to assess clinical durability, cost-effectiveness, and patient-reported outcomes.

Keywords: cochlear implant; electrode array insertion tools; guided system; integrated robots; robotic drilling

Academic Editors: Paul Farago, Sebastian Stefaniga, Robert Radu Ilesan and Sorin Hintea

Received: 10 April 2025
Revised: 27 June 2025
Accepted: 30 June 2025
Published: 2 July 2025

Citation: Ahmed, O.; Wang, M.; Zhang, B.; Irving, R.; Begg, P.; Du, X. Robotic Systems for Cochlear Implant Surgeries: A Review of Robotic Design and Clinical Outcomes. *Electronics* **2025**, *14*, 2685. https://doi.org/10.3390/electronics14132685

1. Introduction

Hearing loss is defined as a reduced ability to perceive sound compared to individuals with normal hearing, typically characterized by hearing thresholds of $\leq$20 dB in both ears. It may be unilateral or bilateral and can impair the perception of conversational and loud sounds [1]. Hearing loss is considered disabling when the threshold in the better ear exceeds 35 dB. Its prevalence increases with age, affecting over 25% of adults above 60. Many individuals with hearing loss depend on spoken language and benefit from hearing aids, cochlear implants, assistive technologies, and captioning services [2].

Universal Newborn Hearing Screening (UNHS) reports that 1 in 1000 newborns have hearing impairment. By ages 9–16, this increases to 2 in 1000. Among adults aged 18–40, 4.6% experience hearing loss $\geq$ 25 dB, rising sharply to 60% in individuals aged 71–80 [3].

The British Cochlear Implant Group (BCIG), comprising healthcare professionals and stakeholders, supports auditory implant services in the UK. As of 2024, 22,065 individu-

als have received cochlear implants. Between 2020–2021 and 2022–2023, the number of implant users increased by nearly 64%, from 848 to 1395 [4]. The National Health Service (NHS) provides assessment, cochlear implant surgery (including Electrode Array [EA] and transceiver placement), rehabilitation, and long-term care. The NHS ensures device safety through UKCA certification and clinical validation [5].

Cochlear implantation involves drilling into the mastoid bone and inserting the EA through the round window membrane into the Scala Tympani (ST). Surgeons aim to avoid complications and preserve facial nerve function. However, the procedure carries risks, including potential damage to inner ear structures such as the basilar membrane [6,7].

To optimize hearing outcomes, surgeons aim to:

- Insert the electrode deeply to capture low-frequency sounds
- Position the electrode close to the modiolus for efficient stimulation
- Preserve residual hearing
- Maximize frequency range coverage
- Minimize insertional trauma

Cochlear implants comprise three primary components: a transmitter, a receiver, and an electrode array as shown in Figure 1. The electrodes are constructed from materials such as polydimethylsiloxane (PDMS) for insulation and platinum–iridium alloys for conductivity and corrosion resistance [8]. Typically, electrode arrays contain between 4 and 22 contacts [9,10]. Anatomical constraints limit the electrode diameter to approximately 2.3 mm and the length to about 30 mm. Insertion through the round window frequently causes excessive bending, which can damage the basilar membrane and lateral wall [8,11]. To mitigate insertion trauma, hydrogel-coated electrodes incorporating fibrin–collagen or dexamethasone coatings have been investigated to reduce inflammation and mechanical stress [12,13].

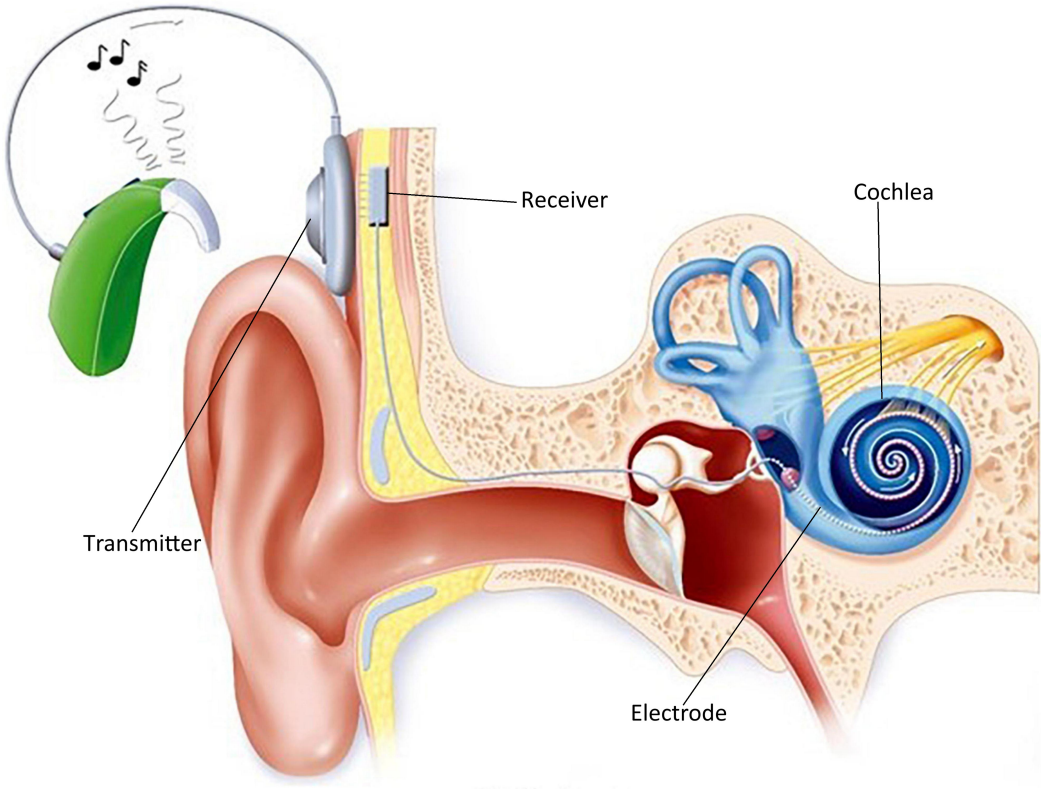

Figure 1. Anatomy of human ear and placement of CI [14].

Robot-assisted CI procedures begin with detailed imaging of the patient's anatomy, typically using CT or CBCT scans. Critical anatomical landmarks, such as the facial nerve and cochlear access points, are identified and marked. On the day of surgery, the surgeon aligns the robotic system with the patient's head. The robot or the surgeon exposes the round window via cochleostomy. The robot then performs the precise insertion of the electrode array. Postoperative imaging confirms accurate electrode placement [10].

Robotic systems enhance cochlear implantation by improving precision, safety, and reproducibility. Preoperative CT scans guide surgical planning, allowing for accurate drilling paths that avoid critical anatomy. Robots dynamically track surgical tools using bone-anchored reference points and adjust in real time based on feedback. They support key steps, such as mastectomy, cochleostomy, and electrode insertion, by reducing trauma and improving outcomes. Systems such as HEARO® and those developed at Vanderbilt enhance procedural consistency, though their impact on residual hearing preservation remains under investigation.

This review evaluates recent advances in robotic cochlear implantation. It discusses system design, surgical integration, clinical applications, outcomes, and challenges. The aim is to assess how robotics may enhance cochlear implant procedures and guide future innovations.

2. Methodology

This paper explores the use of robotic systems in cochlear implantation, focusing on their roles in inner ear access, Direct Cochlear Access (DCA), and electrode insertion. It critically evaluates the design and surgical integration of selected robotic platforms, emphasizing their feasibility for human trials and potential clinical benefits. This review does not encompass all existing robotic systems. Instead, it focuses on a selected subset, offering a detailed analysis of key technologies and surgical techniques.

The authors conducted online searches to identify relevant literature. The databases used included Scopus, ScienceDirect, IEEE Xplore, Web of Science, and PubMed. The selected sources came from peer-reviewed journals such as Frontiers in Neurology, International Journal of Computer Assisted Radiology and Surgery, Applied Sciences, IEEE Robotics and Automation Letters, Otolaryngology–Head and Neck Surgery, and Hearing Research, among others.

Publications were screened for authenticity and relevance, covering studies from 2002 to 2025. The review prioritized recent research (2020–2025) but also included significant works from 2010 onwards. Inclusion criteria required that (i) studies focus on cochlear implantation methods and (ii) full results be available. Review articles were considered to identify trends and synthesize perspectives across the field. Duplicate findings were cross-referenced to identify common patterns. The corresponding data is represented in Figure 2.

Studies published before 2002, extended abstracts lacking results, and non-peer-reviewed data (e.g., company websites) were excluded to ensure source reliability.

The authors conducted this review in accordance with the PRISMA guidelines and followed the PRISMA flowchart methodology. They used multiple search strings to find relevant literature, including:

- `(Cochlear implant* AND robotic system)`
- `(Cochlear implant* AND integrated system)`
- `(Cochlear implant* AND insertion tool for electrodes)`
- `(Cochlear implant* AND HEARO)`
- `(Cochlear implant* AND RobOtol)`
- `(Cochlear implant* AND Vanderbilt)`

- (Cochlear implant* AND ROSA)
- (Cochlear implant* AND review article)
- (Cochlear implant* AND clinical trials)

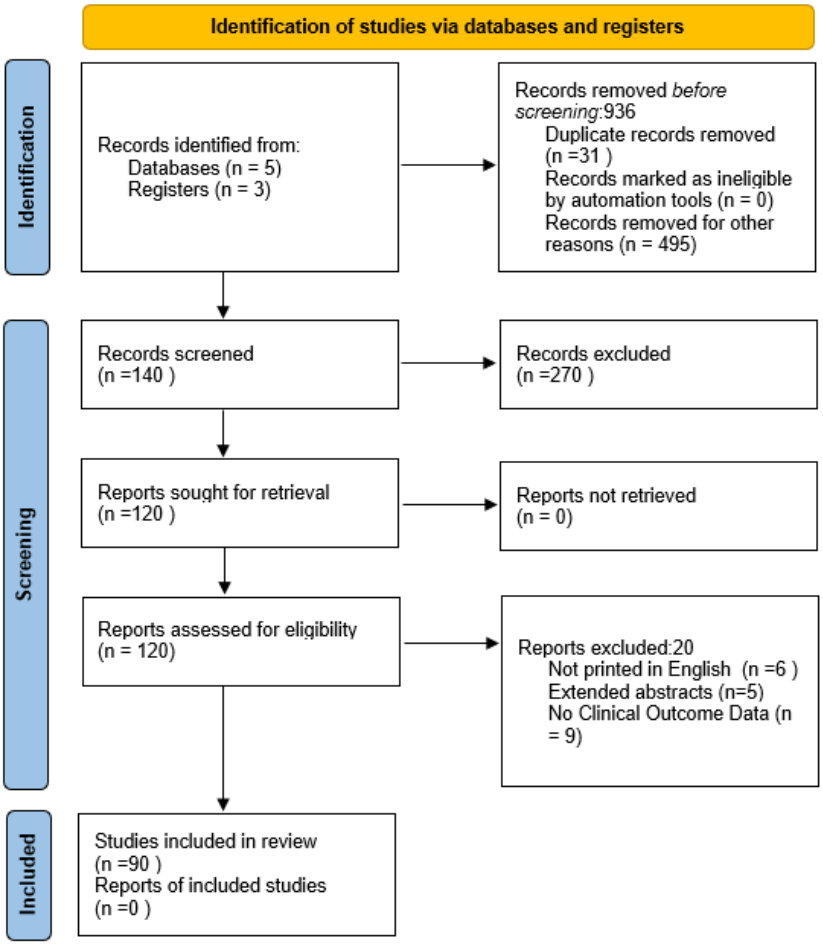

Figure 2. PRISMA flowchart showing the number of searches carried out.

This review systematically examines the integration and clinical implications of robotic systems in cochlear implantation. It highlights how these technologies improve surgical precision, reduce intraoperative trauma, and support hearing preservation. Platforms such as HEARO®, RobOtol®, and the Vanderbilt robotic system are discussed in the context of key surgical stages, including mastoidectomy, cochleostomy, and electrode insertion. Technological innovations like image-guided planning, real-time tracking, and force-controlled drilling are evaluated for their contributions to procedural accuracy, consistency, and safety.

Clinical outcomes such as reduced insertion forces, lower trauma rates, and improved hearing preservation are assessed alongside challenges such as extended procedure time, high costs, training requirements, and anatomical limitations.

Unlike previous reviews, this study integrates both engineering design and clinical performance, directly linking robotic innovation to surgical effectiveness and patient-centered outcomes. It identifies major research gaps, including the need for long-term clinical data, AI-guided navigation, and cost-effectiveness studies. These insights help advance the field toward broader clinical adoption.

Section 3 discusses the mechanical design and testing of robotic systems for inner ear access. Section 4 focuses on robotic contributions to DCA. Section 5 evaluates the use of motorized and robotic tools for electrode array placement. Section 6 summarizes key

findings and assesses the overall impact on hearing restoration. The paper is structured to present information clearly and to highlight research gaps throughout.

No ethical approval or patient consent was required, as this study is based entirely on published literature and did not involve direct experimentation on humans or animals.

3. Robot-Based Approach to Inner Ear

3.1. Robotics for Mastoidectomy (Vanderbilt, USA)

Colleagues at Vanderbilt University (Nashville, TN, USA) developed a surgical robot inspired by CNC milling machines. The system employed brushless DC motors and piezoelectric linear actuators to achieve four degrees of freedom (4-DOF). A Patient Positioning Frame (PPF) ensured precise patient alignment. Safety features included spherical gripper locking mechanisms and handpiece-controlled mobility. Surgeons adjusted the robot and regulated drill spindle speed using a foot pedal. This sterilizable robotic system for mastoidectomy integrated preoperative planning with intraoperative execution. CT scans and fiducial markers synchronized segmentation data with the robot. Surgeons manually identified the bone area for removal, while the robot calculated the milling trajectory using a proprietary algorithm. During surgery, surgeons monitored and adjusted the robot's speed [15,16]. The surgical workflow is illustrated in Figure 3.

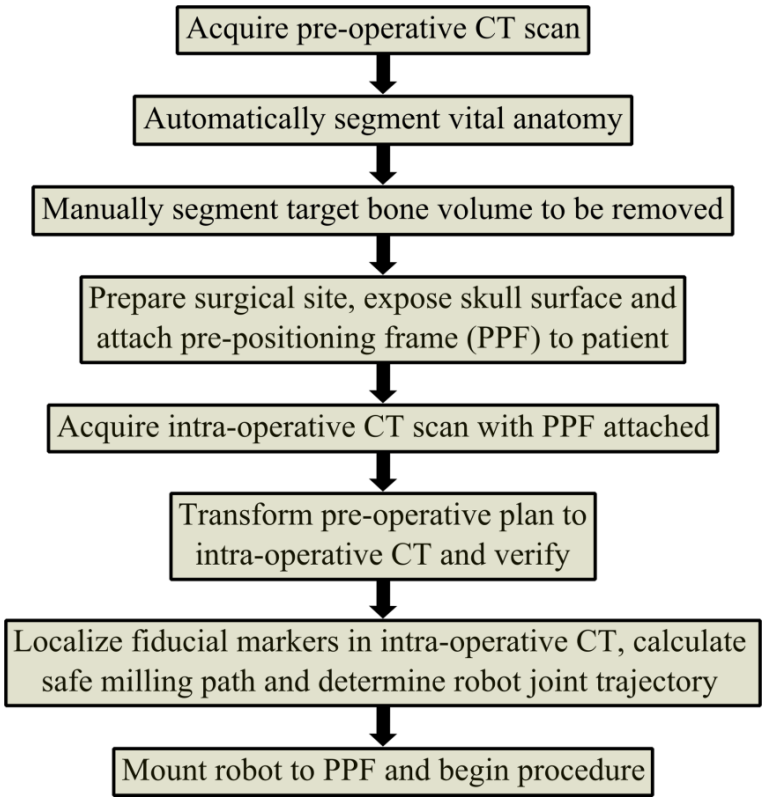

Figure 3. Workflow for surgical procedure [16].

Results: The system's accuracy was assessed at multiple key points near the target bone volume. The mean free space accuracy was 0.50 mm or less across all evaluated sites. A milling test on phantom material validated the surgical workflow. The robot successfully milled within intended boundaries without damaging critical structures [15,16].

Dillon et al. [15,16] identified a research gap regarding piezoelectric actuator resilience to vibrations and high-frequency noise during surgery. The study did not address how varying human bone densities might affect performance. Furthermore, although the authors explored the trade-off between the robot's size and the number of Prepositioning

Frames (PPFs) to improve maneuverability, they did not establish an optimal relationship between these factors.

The Vanderbilt group later introduced a robotic system named OTOBOT. They integrated custom MATLAB® and Simulink software (The MathWorks Inc., Natick, MA, USA) with an industrial Mitsubishi RV-3S robot to precisely control a surgical drill along complex milling paths. A commercial optical tracking system provided real-time feedback, enabling dynamic intraoperative adjustments. Drill paths were pre-planned using CT scans of cadaveric specimens to ensure accurate mastoid bone removal. Bone-implanted fiducial markers facilitated precise registration between CT data and physical space.Results: The system was tested on three cadaver specimens. In each case, a mastoid cavity was milled using a 5 mm fluted ball bit. Postoperative CT scans confirmed accurate ablation of 97.70%, 99.99%, and 96.05% of the target volume without injury to critical structures [17].

3.2. Robotics for Cochleostomy (London, UK)

Cochleostomy is a delicate surgical procedure. Improper drilling can damage internal ear structures, particularly the endosteal membrane. In over 60% of cases, the drill unintentionally penetrates this membrane, leading to potential inner ear injury [18]. To address this issue, Brett and colleagues in London developed a robotic drilling system for cochlear implantation. The system detects tissue interfaces ahead of the drill tip, enabling the identification of critical boundaries. This capability supports tissue preservation, prevents accidental penetration, and allows for real-time feedback for safe drilling control [19].

The system comprises a robotic arm, linear actuator, surgical drill, and computer interface. Integrated motors provide high-precision control [20–22]. Drilling is guided by real-time force and torque (FT) analysis, which applies axial force while maintaining safety limits. Surgeons divide the cochleostomy procedure into distinct stages: drill initiation, full bit engagement, equilibrium drilling, breakthrough onset, and breakthrough completion. These stages are defined by material compliance and cutting resistance, offering a structured approach to the procedure [23].

Despite its advanced design, the system's reliance on FT feedback may reduce sensitivity under varying anatomical conditions. Differences in bone thickness or structural anomalies can impair equilibrium detection and interface identification [23]. However, the system adapts in real time using FT data, enabling intelligent drilling while minimizing risk to delicate structures.

Table 1 presents comparative results from multiple studies. While it does not explicitly consider bone thickness, the consistently lower applied forces suggest a reduced risk of trauma. In follow-up experiments, Du et al. tested the drill on porcine cochleae with varying bone thicknesses. The drill adapted to these changes and prevented rupture of the endosteal membrane. Drilling times ranged from one to ten minutes, with mid-range thicknesses requiring just over two minutes. When force exceeded a 2 N threshold, the system reduced feed velocity to maintain optimal conditions [21].

Table 1. Drilling parameters used in various studies.

Force (N)	Drilling Feed (mm/min)	Drill Speed (rev/s)	Drilling Time (s)	Reference
1.5	0.1	25	30	[24]
-	0.5	10	-	[19]
1.5	0.1	25	30	[23]
-	0.5	10	-	[25]
2	0.1	-	10 min	[21]

Results: Further trials employed a 0.6 mm diamond burr at 7 RPM with CT image guidance. The robotic system created a 0.8 mm-wide bony cochleostomy in 210 s. It

maintained precise control and detected membrane breakthrough within 15 µm. The drill adapted to physiological variations such as respiration and heart rate, both of which are essential for protecting the endosteal membrane during implantation [26,27]. Figure 4 provides a visual representation of the results.

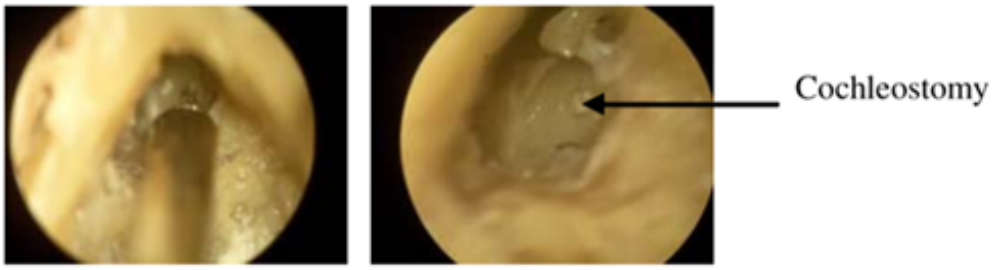

Figure 4. The drill tip at the beginning of cochlear and the resulting cochleostomy (printed with permission) [19].

In collaboration with Caversaccio (Bern, Switzerland), Brett and colleagues further validated the system. They used a 5.5 kg robotic arm mounted on a standard operating table. The setup included a non-invasive head fixation system and a high-precision tracking device (CamBar B1, Axios3D, Germany). The robot followed preoperative drill paths with high accuracy [28]. Inner ear access was achieved with a mean accuracy of 0.08 ± 0.05 mm at the mastoid surface and 0.15 ± 0.08 mm at the cochlear target [29,30]. These results highlight the potential of robotic systems to reduce trauma during cochlear implantation [31].

4. Robots for Direct Cochlear Access (DCA)

4.1. ROSA® (Amiens, France)

Zimmer Biomet Robotics initially developed the ROSA® system for stereotactic neurosurgery. This computer-controlled robotic platform features a 6-degree-of-freedom (DoF) serial manipulator and specialized control software. It enables high-precision procedures, including direct cochlear access (DCA), cochleostomy, and electrode insertion [32].

ROSA® integrates preoperative and intraoperative imaging through the Rosanna® planning software (Zimmer Biomet Robotics, Montpellier, France). Surgeons use this platform to define entry and target points while mapping anatomical landmarks such as the chorda tympani and facial nerve. Fiducial screws are placed around the mastoid to support accurate registration. Continuous electromyography (EMG) monitoring safeguards facial nerve integrity, establishing ROSA® as a viable autonomous system for cochlear implantation (CI) [18]. The setup of ROSA® with fpCT, as employed for neurosurgical procedures, is depicted in Figure 5.

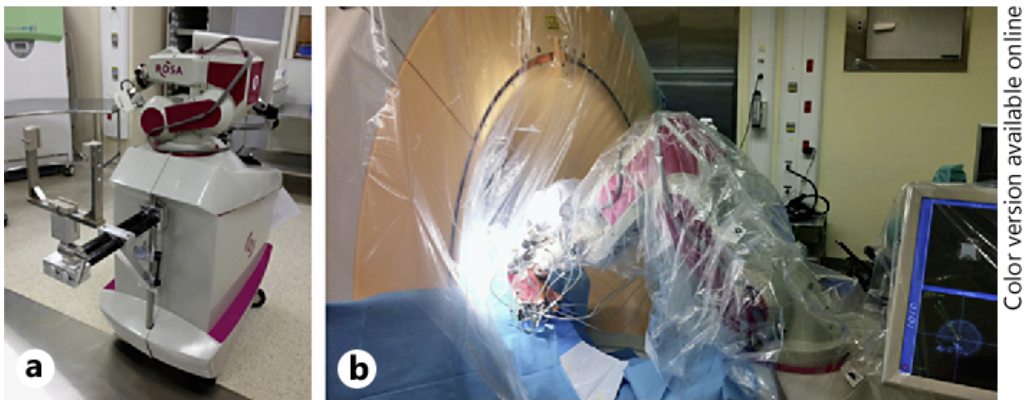

Figure 5. The ROSA® robot (**a**) and in use during deep brain surgery (**b**) integrated with an fpCT system [32].

ROSA® was introduced over a decade ago and initially validated through phantom studies at 20 anatomical sites using both frameless and frame-based registration [18]. Subsequent clinical trials involved fewer than five patients, focusing on temporal bone procedures.

Results: The surgical workflow begins with preoperative CT-based planning. Surgeons map a 2.5 mm drilling trajectory through the facial recess, avoiding critical structures with real-time EMG monitoring. The patient's head is fixed, and five fiducial screws are positioned around the mastoid for image registration. Intraoperative CT data are fused with preoperative scans, achieving a fusion error of less than 0.35 mm.

A retroauricular approach is performed, followed by the placement of a robotic arm reducer along the planned drill path. Drilling begins with a 5 mm multipin bit and continues with progressively smaller drills (3.2 mm, 2.5 mm, and 1.5 mm) for cochleostomy. Software continuously tracks the drill's proximity to the facial nerve. Finally, the robot inserts the electrode array using a micro-descender. The full procedure takes approximately six hours [18,33,34].

The extended surgical duration underscores the need to improve system efficiency and reduce operative time. Enhancing workflow optimization remains essential for maximizing the benefits of robotic integration in cochlear implantation.

4.2. HEARO® (Bern, Switzerland)

Caversaccio and colleagues developed a head fixation mechanism using fiducial markers to ensure accurate localization and stability during cochlear implantation [35,36]. During preoperative planning, surgeons perform semi-automatic segmentation of anatomical structures, including mapping the course of the chorda tympani. Specialized software generates the drill trajectory automatically. The system includes a 5-DoF serial robotic arm mounted on the operating table, equipped with a surgical drill for both cochleostomy and electrode array (EA) insertion. Intraoperative imaging is facilitated by an optical stereo camera [37]. The clinical setup is demonstrated in Figure 6.

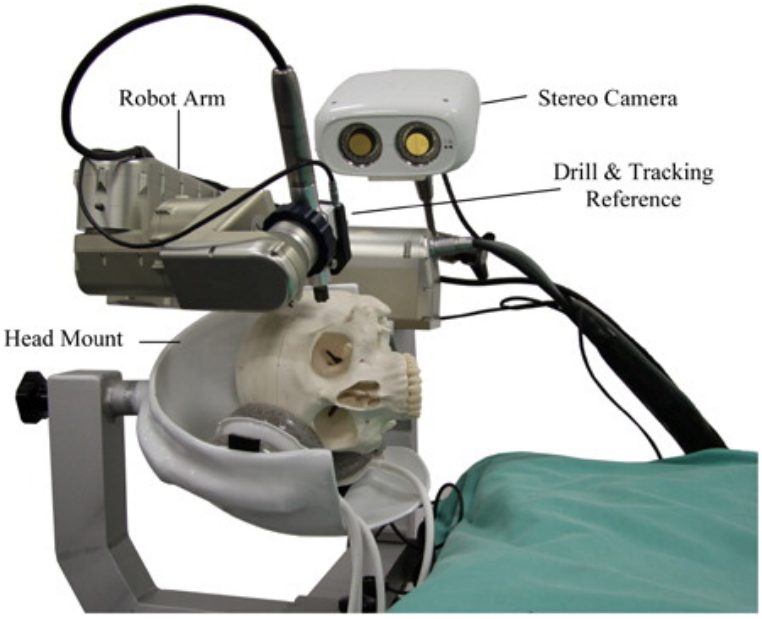

Figure 6. The surgical robot is mounted on the operating table, with the patient's head stabilized in a non-invasive clamp [35].

Prior to cone beam CT (CBCT), clinicians place four mastoid screws under local anesthesia. This setup achieves a clinical accuracy of 0.21 ± 0.09 mm in a cohort of nine patients.

Two intraoperative CBCT scans are used to verify alignment [38]. A study involving 50 patients (100 ears) further evaluated the feasibility of robotic cochlear implantation using high-resolution CT and CBCT. The researchers analyzed trajectory planning and assessed optimal drill diameters, including the standard 1.8 mm bit [18,36,37,39,40].

In this context, the OTODRIVE® system was precisely aligned with HEARO®. The team ensured accurate setup for a 28 mm intracochlear array and a 31 mm insertion tube. Electrode insertion was automated at a controlled speed of 0.1 mm/s. Simultaneously, a protective channel was drilled into the mastoid cortex to accommodate the electrode lead [41].

These technological advancements have translated into successful clinical outcomes. For instance, the HEARO® robotic system was recently utilized in a 76-year-old female patient with age-related sensorineural hearing loss. Intraoperative measurements recorded distances of 0.48 mm to the facial nerve and 0.79 mm to the chorda tympani. The surgical team achieved precise inner ear access, visualized the round window via a minimally invasive keyhole trajectory, and carefully perforated the membrane using a micropique [41].

The authors concluded that robotic systems exceed manual dexterity by standardizing insertion angle and speed. While manual insertion may reach speeds of up to 0.87 mm/s, the HEARO® system maintains a consistent speed of 0.1 mm/s. This significantly reduces intracochlear pressure and supports the preservation of residual hearing [41].

4.3. Vanderbilt Group (Nashville, USA)

Labadie et al. at Vanderbilt University developed a bone-attached parallel robot designed for precise cochlear implant surgery. This system employs a patient-specific micro-stereotactic frame, which is affixed to the skull via three rigid titanium bone anchors with spherical tips. These anchors function both as fixation points for the stereotactic frame and as fiducial markers for registering patient anatomy to preoperative computed tomography (CT) scans. Preoperative CT images are utilized to segment relevant anatomical structures and to delineate safe linear trajectories targeting the scala tympani [18].

Intraoperatively, a customized drill press is mounted on a small tabletop fabricated on the basis of fiducial marker positions. An intraoperative cone-beam CT (CBCT) scan is acquired to register the segmented anatomy and planned drilling trajectory to the patient's current position. This is shown in Figure 7. The cochlear access tunnel is then drilled with diameters varying from 3.8 mm lateral to the facial nerve to 1.59 mm adjacent to the facial recess. The accuracy of the drilled tunnel is verified through intraoperative CT imaging followed by endoscopic inspection. To facilitate access to the middle ear, a tympanomeatal flap is elevated to permit a direct cochleostomy under visual guidance. Subsequently, the electrode array (EA) is inserted through the drilled tunnel into the cochlea, and its placement is confirmed by a final intraoperative CT scan, thereby ensuring surgical precision and effectiveness [18,42–44].

Results: A preliminary clinical feasibility study involving 13 pediatric cochlear implant (CI) recipients demonstrated that the micro-stereotactic frame allowed for precise cochlear trajectories while successfully avoiding critical anatomical structures such as the facial nerve and chorda tympani [45]. The frame was securely anchored in nine patients, including two with inner ear malformations, and the cochleostomy site was confirmed intraoperatively. In patients with normal anatomy, the mean closest distances to the facial nerve and chorda tympani were 1.1 ± 0.3 mm and 1.2 ± 0.5 mm, respectively. Furthermore, in a separate cohort of nine adult patients, electrode array insertion was successful in eight cases, with an average surgical duration of 182 ± 36 min [18].

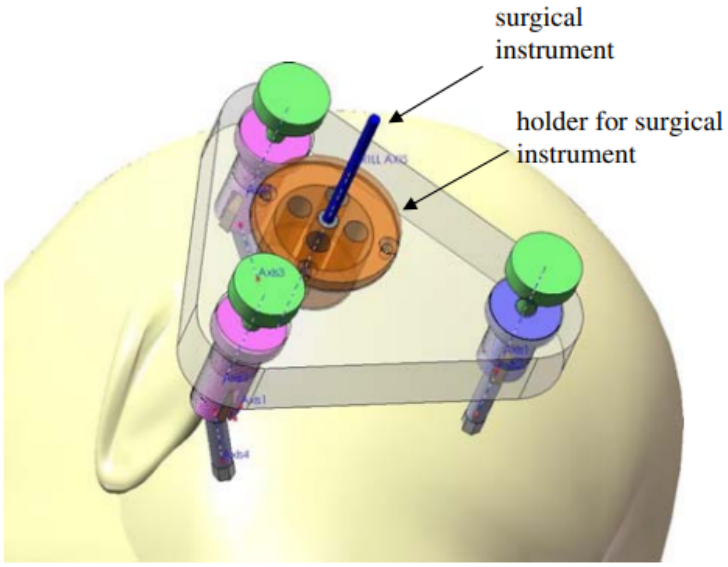

Figure 7. A microtable is secured to the patient, with a surgical instrument mounted on the tabletop via a holder [42].

Despite promising results, one patient developed permanent moderate facial nerve palsy, which prompted regulatory restrictions under the Food and Drug Administration Safety and Innovation Act (FDA). To mitigate this risk, modifications were made to the drill design, and a custom insertion tool was developed. Subsequent to FDA approval of the revised protocol, a clinical trial was successfully completed in a 70-year-old patient. The duration of the procedure was 155 min [46].

The results from all robotic systems included in this review are summarized in the Table 2, along with their key performance indicators.

Table 2. Robots for DCA.

Robot Type	Guiding System	Drill Path Trajectory Planning	Clinical Trials	Kinematic Structure	DoF	Time Needed for Surgery (min)	Accuracy of Insertion (mm)	Reference
Rosa® (Amiens, France)	CT scan, MRI, fpCT	Rosanna® software	Yes	Serial	6	120	0.3, 1.59	[32]
HEARO® (Bern, Switzerland)	IGS	Custom-built software	Yes	Serial	6	300	0.15 ± 0.08	[35]
Microtable® Vanderbilt (Nashville, TN, USA)	CT Scan	Custom-built software	Yes	Parallel	6	60	0.37 ± 0.18	[42]
Hexapod (Hannover, Germany)	CT Scan	Custom-built software	Yes	Parallel	6	156	0.36 ± 0.12	[47]
OtoJig® (Hannover, Germany)	CBCT	Python programming language (2.7)	Yes	-	-	-	0.30 ± 0.11	[48]
GluingJig® (Hannover, Germany)	CBCT	Python programming language (2.7)	Yes	-	-	-	0.30 ± 0.11	[48]

4.4. Robots for Accessing Trans Mastoid

Hexapod and Micro-Stereotactic Frames (Hannover, Germany)

Researchers at Hannover Medical School in Germany, including Lenarz, Majdani, Ortmaier, and colleagues, developed two robotic systems for minimally invasive inner ear access:

- Custom-Made Parallel Kinematics Motion Device (Hexapod):
  The Hexapod system features optimized structural elements and passive legs equipped with micrometer gauges. Surgeons mount the device directly onto the skull using magnetic bearings. The latest design includes a spherical platform with three non-rigid bone anchors, allowing for individualized placement based on patient anatomy.
  Results: The system enables straight-line trajectory guidance. Tests on temporal bone models demonstrated a target accuracy of 0.36 ± 0.12 mm [47,49].
- Customized Targeting Platforms:
  This system consists of a reusable base frame and a disposable, patient-specific surgical guide. It provides a mechanical interface for a linearly guided surgical hand drill, enabling precise positioning. The RoboJig® research project validated its preclinical feasibility. Intraoperatively, clinicians shape disposable templates using bone cement, a sterile and clinically accepted material that allows for rapid customization [18].

One model uses a mechatronic positioning system that adjusts plates to create an optimal drill trajectory. Surgeons secure the system using silicone hoses filled with bone cement [50]. A recent design incorporates a passive hexapod with manually adjustable legs to hold the surgical template until the cement cures. After assembly, the template is connected to a pre-registered Trifix base frame and anchored to the skull [51]. This is shown in Figure 8.

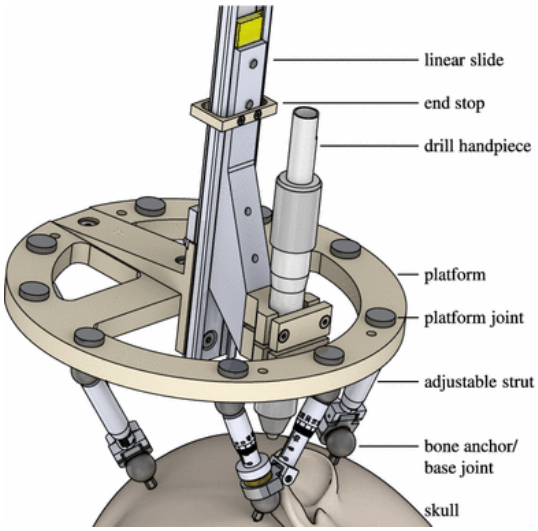

Figure 8. A bone-mounted parallel robot designed to guide instruments along a precise straight-line path for CI [47].

The Hannover team also contributed to the development of the GluingJig and OtoJig® systems. Both were designed to enhance precision in cochlear implant surgery. The GluingJig system employs parallel kinematics to improve tool positioning and reduce human error [48]. A micro-stereotactic targeting system was developed, combining a reusable bone-anchored reference frame with a patient-specific drilling jig, achieving high accuracy (0.09 ± 0.03 mm, measured via CMM). However, limitations in fixation stability were observed in patients with thicker skin, along with potential frame movement. To address these issues, the integration of parallel kinematics was proposed to further improve insertion

precision. In parallel, the OtoJig® system was evaluated using a 1.5 mm sham drill bit in six patients. Despite its success with smaller drill bits, the use of a 1.8 mm bit resulted in failures in three cases due to anatomical constraints. The system employed a single bone screw for fixation, and the Screw Implantation Safety Index confirmed the safety of using 4 mm screws [52].

5. Electrode Insertion Tools

5.1. Motorized Electrode Insertion Tools (Hannover, Germany)

Hussong et al. designed shortened forceps to hold and retract the platinum wire stylet via a wire hook, ensuring precision and stability through piezoelectric technology. The device employs gearless linear drives that offer exceptional control, thus achieving positional accuracy of 1 µm and speeds as low as 5 nm/s. Sequentially arranged actuators enable independent control of electrode advancement and stylet retraction. A U-shaped tube serves dual functions as an electrode shield and drill guide, accommodating standard drill canal diameters of 1.5 to 2.3 mm. Surgeons use dedicated software on a conventional PC to perform personalized insertions, allowing for manual drive movements in 0.1 mm increments and adherence to pre-planned trajectories, thereby, minimizing mechanical stress and improving patient-specific outcomes [53]. The set up is shown in Figure 9.

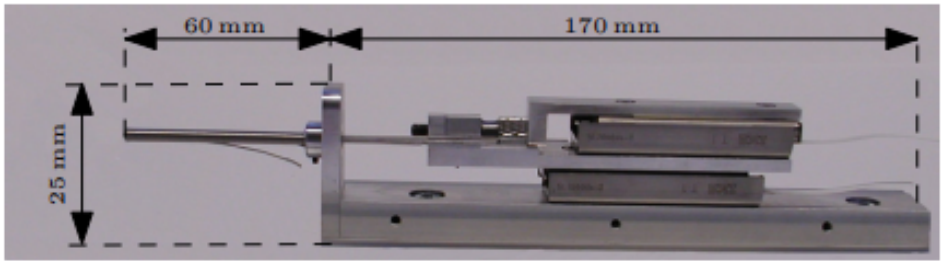

Figure 9. Automated insertion tool design by [53].

A major limitation of this system is the absence of haptic feedback. Manual insertion techniques rely on tactile cues to detect complications such as tip fold-over or intracochlear resistance. Without such feedback, the system lacks the adaptive capacity necessary for real-time correction.

Hussong et al. [53] observed that, in well-lubricated models, insertion depth angle was limited solely by electrode feed, confirming that lubrication effectively reduces friction and insertion forces. This reduction decreases the risk of trauma and improves the chances of preserving residual hearing. Insertion speed also plays a critical role; lower speeds are associated with reduced intracochlear pressure, protecting delicate structures and improving audiological outcomes [54], as shown in Table 3.

Building on Hussong et al.'s work, the same group integrated a force sensor into the existing tool design [55,56]. They embedded semiconductor strain gauges with 50–75 times the sensitivity of traditional gauges, enabling detection of forces in the 0–0.05 N range with 0.005 N resolution. A Wheatstone bridge circuit compensates for thermal drift, while a flexible beam structure limits deflections to 0.5 mm. Calibration tests confirmed ±0.003 N accuracy, ensuring reliable real-time force monitoring. **Results:** The force sensor enables an automated insertion system integrated into Vanderbilt's Micro-Stereotactic Frames for image-guided surgery. A study of 13 patients (18 ears) undergoing traditional cochlear implantation demonstrated that surgeons successfully accessed the cochlea via the facial recess in all cases, maintaining an average drill-to-facial nerve distance of 1.20 ± 0.36 mm and 1.25 ± 0.33 mm from the chorda tympani [42,43,57].

Table 3. Description of different lubricants used in studies.

Study	Lubricant	Insertion Depth	Insertion Time (s)	Speed (mm/s)	Reference
CHD	Water	45 mm	<60	0.03	[58]
Manual roller wheel	Soapy water	12/12 electrodes inserted	99 ± 28	–	[59]
Manual insertion	Sodium hyaluronate	289 ± 35.0 (deg)	36 ± 7	–	[60]
RobOtol	Sodium hyaluronate	328 ± 19.3 (deg)	80–100	0.25	[60]

5.2. Cochlea Hydro Drive (CHD (Hannover, Germany))

The Cochlea Hydro Drive (CHD) prototype employs a modified syringe to achieve precise linear movement during electrode array (EA) insertion [58,61]. This system integrates flexible tubing to connect a disposable syringe with an external infusion pump, converting hydraulic pressure into controlled linear displacement. By positioning critical components outside the sterile field, the CHD eliminates sterilization requirements and improves cost-effectiveness. The infusion pump features adjustable flow rates, enabling surgeons to precisely control insertion velocity according to varying surgical conditions. Safety mechanisms include a three-way stopcock valve, sterile adapters, and a U-shaped probe holder, which ensure device reliability. The design of CHD device is shown in Figure 10. Researchers propose polyether ether ketone (PEEK) for improved sterilization. Integrated force sensors monitor insertion forces and normalize force profiles across trials. **Results:** The forces progressively increase with deeper EA insertion, with recorded average maximum forces of (0.060 ± 0.007) N at 0.03 mm/s and (0.107 ± 0.036) N at 0.4 mm/s insertion velocity [58].

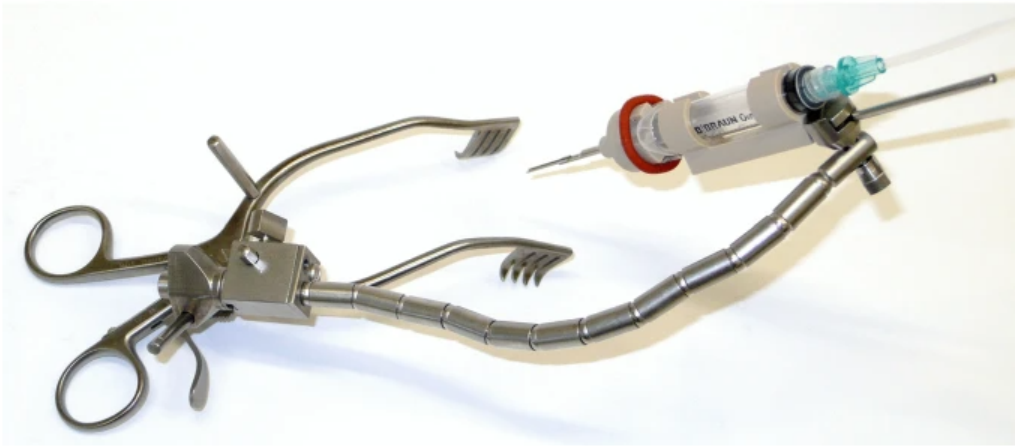

Figure 10. Prototype for CHD [58].

To further improve accuracy and minimize trauma risk, researchers integrated the Cochlea Hydro Drive (CHD) with a force sensor, also referred to as the hydraulic actuation system [62]. A comparative study measured forces during automated and manual insertions into an artificial cochlea model using a static external force sensor [63]. Additionally, two CI surgeons performed insertions of commercially available electrode arrays (EAs) into three temporal bone specimens while capturing insertion forces, tool orientation, and camera footage. The surgeons successfully completed all 18 trials, with the surgical workflow aligning with standard CI surgery. They recorded an average peak insertion force of 62.4 mN ± 26.7 mN, showing a strong correlation between peak forces and final electrode depth, which confirms that measured forces primarily reflect intracochlear events.

Gravity-induced forces of up to 28.8 mN were found in the data. In vivo testing demonstrated feasibility, with insertion forces increasing predictably from 17.2 mN to 43.6 mN and peak forces ranging between 44.8 mN and 102.4 mN [64].

The CHD remains a simple yet robust tool with promising results. However, it lacks automated backward motion, which limits surgeons' flexibility for retraction and error correction during surgery. Furthermore, researchers have not yet clarified its impact on long-term outcomes such as hearing preservation and electrode stability. These factors warrant further discussion. Integrating a force sensor into the CHD device enhances the interpretability of in vivo insertion force data in laboratory settings. Providing surgeons with real-time insertion force feedback could further improve residual hearing preservation, though clinical studies have not yet conclusively demonstrated this.

5.3. Roller Wheel Mechanism (Vanderbilt, USA)

Narishman et al. introduced a roller wheel mechanism within the insertion tool. This mechanism produces a 0.80 mm mid-channel contraction by converting rotational motion into axial displacement via friction with the EA's silicone sheath. The proximal end features a rigid roller replicating the drilled channel's geometry. The distal polyimide tube maintains dimensional precision in the medial drill channel. The tool, 3D-printed from biocompatible, autoclavable dental resin, consists of two screw-fastened halves that surgeons can disassemble as shown in Figure 11. The polyimide tube prevents buckling. Patient images obtained through an imaging technique guided the insertion process. Trials comparing this tool to surgical forceps using a Med-El standard EA demonstrated a 26-second reduction in insertion time, improved full insertion rates (6/6 vs. 1/6), and elimination of buckling (0/6 vs. 5/6) [59,65].

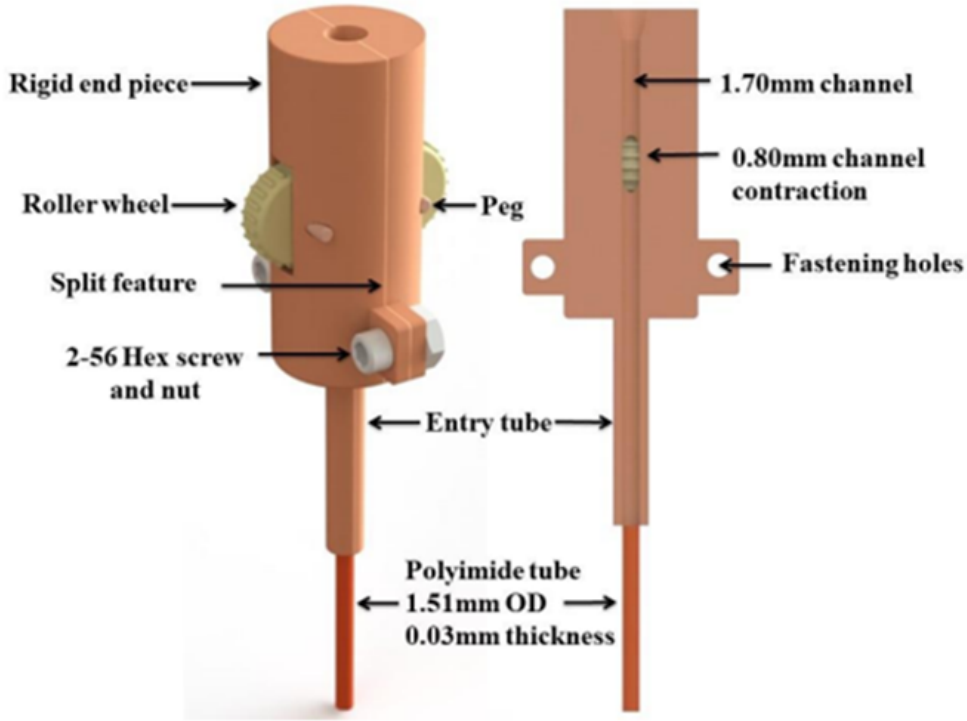

Figure 11. Prototype of the roller wheel mechanism [59].

Subsequent refinements included a slit polyimide disassembly method to improve concentricity. A second tongue-and-groove feature on the guide cylinder, and component miniaturization to meet surgical constraints. This disassembly method allows surgeons to sequentially remove tool halves, extracting the polyimide-attached half via a helical slit

to prevent EA displacement. The tool's two interlocking 3D-printed halves incorporate roller wheels for precise EA advancement. It is tailored for MED-EL Standard and FLEX series EAs, accommodating a 1.3 mm silicone sheath and a 1.4 mm stopper ring that signals insertion depth. Surgeons thread the EA through the tool lumen, where roller wheels engage the transmitting wire to control insertion. Fabrication was standardized using an assembly jig and fully 3D-printed components to ensure precision [66].

Results: Following FDA approval, clinical data confirmed successful threading of a MED-EL FLEX28 EA through the drilled tunnel into the cochlea after receiver placement. The tool enabled full insertion, positioning all 12 electrodes intracochlearly within the scala tympani and achieving a final angular insertion depth of 557 degrees post-removal [66]. In another study, ref. [67] integrated the roller mechanism with a pressure sensor, measuring a peak pressure of 133 Pa at a 0.15 mm/s insertion speed. Although this approach advances navigational systems by combining pressure sensors, force sensors, and imaging, the experiments were not conducted under ideal or phantom conditions, limiting definitive conclusions.

5.4. Magnetically Steered Robotic Insertion (Vanderbilt, USA)

Burns et al. combined magnetic steering with image-guided techniques to achieve electrode array (EA) insertion. Magnetic fields significantly reduced insertion forces, lowering the risk of intracochlear damage and procedural errors. The study introduced two key advancements: (i) a novel nonmagnetic insertion tool, and (ii) Omni magnet, an electromagnetic device that provides programmable magnetic field control to enhance patient safety. Experiments were conducted on phantom models and formalin-fixed cadaver cochleae [68].

Patient-specific plans were generated from preoperative CT scans. These plans guided optimal insertion vectors, tool poses, Omni magnet positions, and magnetic field orientations tailored to individual anatomy. The Omni magnet features a ferromagnetic core and three nested orthogonal coils, enabling precise magnetic field generation without physical magnet movement. The insertion tool was fabricated from Nitinol tubes, piezoelectric linear actuators, and a 3D-printed housing to ensure precise manipulation and minimize trauma to cochlear structures [68].

Results: Magnetic steering reduced insertion forces by 48.8% in cadaver insertions and 53.8% in phantom insertions compared to robotic insertion alone. Force data from manual cadaver insertions provided additional comparison. Magnetic steering also enabled greater angular insertion depths in phantom models than robotic-only or manual methods, demonstrating its potential to improve cochlear implant placement [68].

In related work, Bruns et al. [68] confirmed that robotic insertion of magnetically steered lateral wall EAs lowered insertion forces in vitro and in cadavers. However, the direct effect of these forces on the basilar membrane remained unexplored. Hendricks et al. [69] addressed this by performing insertions in an open-channel scala tympani phantom equipped with a force plate simulating the basilar membrane. An electromagnetic source provided magnetic steering of investigational EAs fitted with permanent magnets at their tips, while a robotic system controlled insertion.

Results: When magnetic steering successfully lifted the EA tip from the lateral wall, forces on the phantom basilar membrane decreased by at least 62% at insertion depths beyond 14.4 mm ($p < 0.05$). This reduction persisted despite modiolar axis estimation errors up to 10 degrees. Conversely, failure to reposition the EA tip resulted in no significant force difference compared to non-steered insertions. Nonetheless, potential interference between the magnetic fields of the cochlear implant device and insertion tool remains a

concern. Misalignment could impair trajectory accuracy. Ongoing research focuses on optimizing this integration for clinical adoption [70].

A detailed comparison of the insertion tools analyzed in this review, highlighting their critical parameters, is presented in Table 4.

Table 4. Robots for electrode insertion.

Robot Type	Clinical Trials	Insertion Speed (mm/s)	Insertion Time (s)	Reference
RobOtol®	Yes	0.1	73 ± 10	[71]
iotaSoft®	Yes	0.1–1	195 (3 m 15 s)	[72,73]
OtoDrive®	Yes	0.3	98 ± 35, 103 ± 19	[74]
Cochlea Hydro Drive	No	0.02–0.9	315	[61]
Roller Wheels Tool	Yes	-	-	[66]
Magnetically Steered Robotic Insertion	No	0.3–1.25	22.4, 103 ± 19	[68,69]

5.5. Robot-Assisted Electrode Insertion

5.5.1. RobOtol® (Paris, France)

RobOtol® is an industrial teleoperated robotic arm with six degrees of freedom (DOF), designed for precise electrode insertion through the external ear, particularly in constrained surgical environments [75]. The system integrates a micro-instrument and endoscope holder, enabling minimally invasive cochlear implant (CI) surgery. It features a high-precision XYZ cross-table formed by a Z-axis linear stage with 95 mm travel and two orthogonal X–Y stages, each with 70 mm travel. Rotary motion is controlled by three DC micromotors with magnetic incremental encoders and a 100:1 reduction ratio. Surgeons operate the system via a SpaceMouse using a position-to-velocity control scheme. Safety is ensured by a registration mode that decouples robot and master arm configurations. A dead man's foot switch (DMFS) prevents unintended movement. RobOtol® aligns motorized insertion tools accurately to enable electrode insertion through the round window at a controlled speed of 0.3 mm/s [18,60,76].

Results: Developed by UMR-S 1159 and Collin© Company in 2006, RobOtol® was commercialized in 2016 and introduced clinically across Europe and China in 2019 [71]. It supports electrode insertion tools compatible with Cochlear™, Advanced Bionics®, Oticon Medical®, MED-EL®, and Nurotron® devices [18]. A clinical study in Paris involving 20 patients demonstrated that robot-assisted insertions reduced electrode translocation rates to 7%, compared to 16% in manual procedures ($p < 0.001$). However, total surgical time, including mastoidectomy and posterior tympanotomy, averaged 138 ± 7.1 min, which is approximately 30 min longer than manual surgery (109 ± 4.0 min) [77].

5.5.2. iotaSoft® (Iowa, USA)

The iotaSoft® system (iotaMotion Inc., Iowa City, IA, USA) is cleared by the FDA for use with modern lateral-wall electrode arrays. It enables lower insertion forces and reduces trauma compared to manual techniques by operating at controlled, slower speeds. Precision is further enhanced when surgeons employ real-time electrocochleography feedback [78].

The system consists of a sterile, single-use drive unit connected to a reusable, non-sterile touchscreen control console and foot pedal interface. This is shown in Figure 12. Surgeons secure the drive unit to the squamous cortex of the temporal bone using two self-tapping bone screws via a standard mastoidectomy/facial recess approach. Alignment is achieved through multiple locking positions. A semi-flexible "gooseneck" arm stabilizes the drive head by applying calibrated pressure to the electrode array between two drive wheels. Under an operating microscope, the surgeon adjusts the drive head to maintain

clear visibility of the round window. Insertion speed is adjustable between 0.1 and 1 mm/s to accommodate surgical preferences and procedural requirements [72]. Sterile and non-sterile components are coordinated to maintain sterility and prevent contamination.

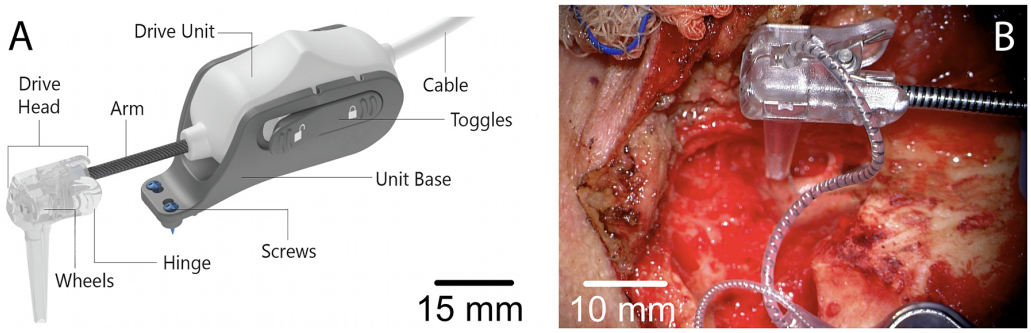

Figure 12. (**A**) iotaSoft for robotic electrode insertion. (**B**) Intraoperative microscopic image showing the electrode array insertion device equipped with a cochlear implant electrode array [72].

Results: In preclinical trials, researchers performed cochlear implant electrode insertions on 24 fresh-frozen human cadaveric cochleae using either manual techniques (n = 12) or a robotic-assisted system (n = 12). The robotic system produced significantly lower insertion forces and reduced variability compared to manual insertions. Trauma assessments showed higher scores for manual insertions (3.1 ± 2.0) than robotic-assisted insertions (0.9 ± 1.0), indicating reduced trauma with robotic assistance [73].

In a clinical study conducted between September 2020 and January 2021, 25 participants who met FDA criteria for cochlear implantation were evaluated. The device base was secured in an average of 33.3 s, and full insertion took 2 min and 31 s, which was 45 s faster than manual procedures [72].

Another study involving 21 postlingually deaf adults used real-time electrocochleography during robotic insertion. Results demonstrated stable postoperative pure-tone averages, normal impedance levels, and consistent neural telemetry responses [79].

5.5.3. OtoDrive® (Bern, Switzerland)

Aebischer et al. introduced OTODRIVE (CASCINATION AG, Bern, Switzerland). This robot-assisted cochlear implant insertion system comprise four main components: an experimental model simulating surgical conditions, a positioning arm, an alignment unit (OTOARM Aligner), and a linear actuator (OTODRIVE Handpiece) controlled via software and a foot pedal as shown in Figure 13.

Results: In an in vitro study, the surgical team fixed the OTOARM to the operating table and assembled the OTOARM Aligner, OTODRIVE handpiece, Connector OD, and Forceps OD. The Forceps OD was initially positioned at 40 mm to align the insertion trajectory, then retracted to 0 mm to mount the electrode. Electrodes were inserted at a controlled speed of 0.1 mm/s, and insertion halted upon full insertion or buckling. Postoperative CT imaging combined with OTOPLAN software (V5 3.1.0) analyzed insertion angle, cochlear coverage, tip fold-over, scala deviation, and complications. The team noted challenges including setup complexity and obstructed surgical views [80].

In a separate study, sixty insertions using MED-EL Flex28 electrodes were evaluated. Data processing employed OpenCV for image tracking and Python's SciPy for statistical analysis. Robotic assistance significantly reduced force variability and intracochlear pressure peaks, lowering pressure by 17 dB relative to manual insertions, which leads to reduced cochlear trauma. Although periodic realignment was necessary, the system achieved a median insertion depth of 558° with no significant differences in depth or duration compared to manual procedures [74,80].

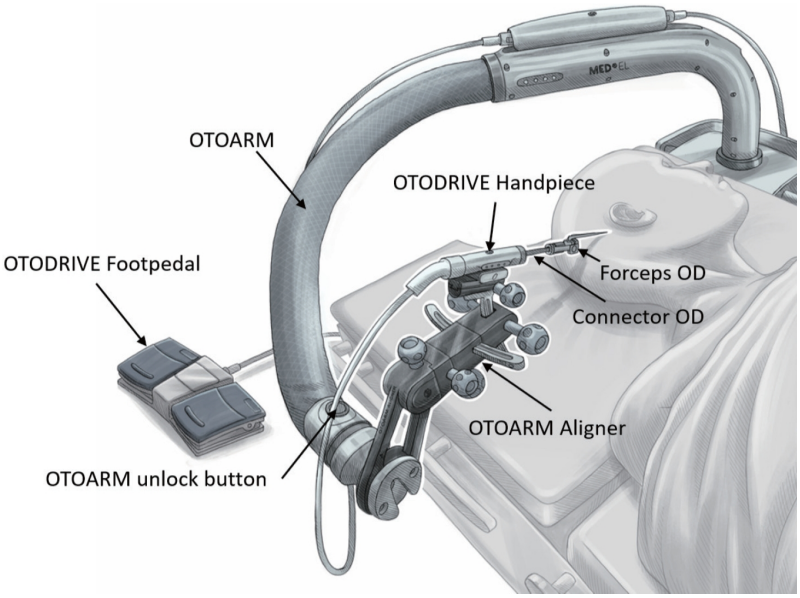

Figure 13. Setup for OtoDrive® [74].

In 2025, Aebischer et al. proposed a reusable insertion tool integrating a force sensor for real-time force measurement. The device includes a base mount for fixation stability, normally closed forceps for electrode handling, a motorized rail for controlled advancement, and a force-measuring adapter sampling at 25 Hz with a force resolution of 0.53 mN. Testing on six cadaveric specimens confirmed full electrode insertions and accurate placement verified by post-implantation CT scans. Recorded insertion forces averaged 69 ± 26 mN, with deviations primarily due to anatomical obstructions. The head-mounted fixation design minimizes micromovements and allows for patient repositioning during surgery [74,81].

OtoDrive® offers clear advantages over manual methods by reducing intracochlear pressure and force variability. Accuracy is further enhanced through AI-based data analysis. However, the system currently measures force only along a single axis, omitting torque and rotational forces that may affect insertion quality. Additionally, it lacks automation for post-insertion tasks such as electrode cable routing and sealing, limiting its full clinical integration. These promising advancements warrant further development to realize a fully integrated robotic cochlear implantation solution.

6. Discussion

Cochlear implantation (CI), a standard treatment for profound hearing loss, has evolved significantly since the 1970s [82]. Over the past two decades, robotic-assisted CI surgery has gained traction. This is demonstarted in Figure 14. Surgeons and researchers increasingly adopt robotics to enhance precision, reduce trauma, and improve patient outcomes [82]. Key success factors include hearing preservation, trauma reduction, and accurate electrode placement [83]. Innovations in Robotically Assisted Cochlear Implantation Surgery (RACIS) encompass image-based surgical planning, intraoperative guidance, minimally invasive keyhole access, robotic electrode insertion, manipulators, and drilling feedback control. These advances aim to improve surgical consistency and electrode placement accuracy [84].

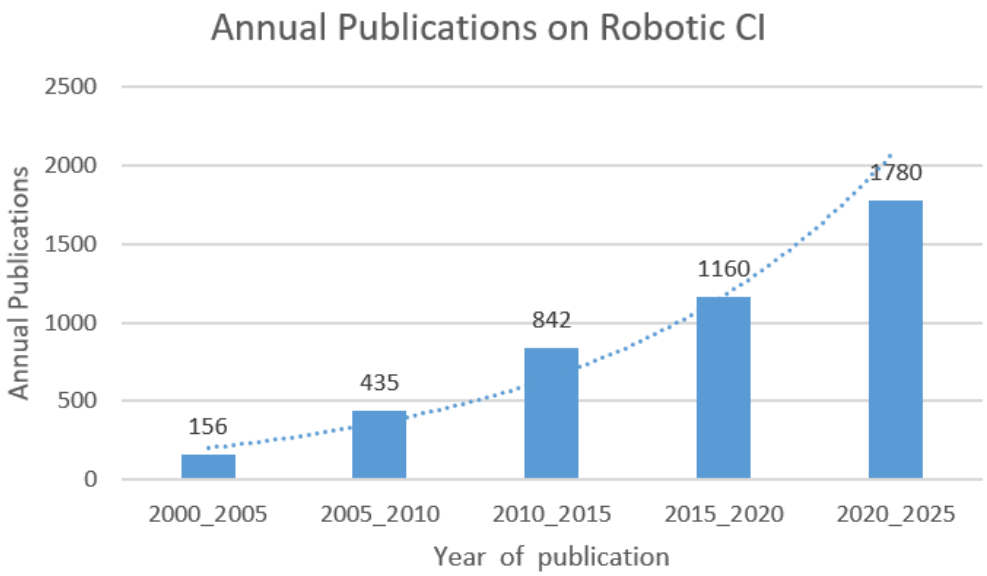

Figure 14. Annual publications reported on robotic cochlear implantation from 2000–2025.

This review examines robotic systems used in CI, including tools for middle ear access, Direct Cochlear Access (DCA), and motorized electrode insertion. The Vanderbilt, Hannover, and Bern groups have made significant contributions to robotic DCA and insertion, while the London group leads in robotic drilling. Some systems such as Vanderbilt's platform, the CHD device, and iotaSoft® have progressed to clinical trials and have received FDA approval. Two commercial systems, iotaSoft® (iotaMotion Inc.) and RobOtol® (Collin), are currently in clinical use [80].

The primary objective of cochlear implant (CI) surgery is the atraumatic insertion of the electrode array (EA). This requires minimizing mechanical stress during implantation. Controlled insertion speed is critical, as it reduces insertion forces and limits intracochlear pressure spikes [54,85]. Insertion forces typically result from contact between the EA and anatomical structures such as the lateral wall, basilar membrane, and osseous spiral lamina [86].

Rajan et al. and Sykopetrites et al. both emphasize the benefits of slow, controlled electrode array (EA) insertion in cochlear implantation. However, Rajan et al. provide a more direct causal link. They inserted identical electrodes at two defined speeds: 0.25 mm/s (slow) and 1 mm/s (fast). Controlling for other variables, they showed that slower insertion significantly improved postoperative outcomes. Specifically, slow insertion better preserved residual hearing, allowed for more complete insertions, and reduced vestibular symptoms within 24 h. Their results demonstrate that insertion speed alone critically influences trauma reduction and recovery [87].

Sykopetrites et al. compared robotic and manual insertions in pediatric patients, focusing on insertion speed and electrical performance. RobOtol® achieved a slower mean speed of 0.3 mm/s versus 0.52 ± 0.17 mm/s for manual insertions ($p = 0.0055$). This slower speed correlated with lower impedance at activation (9.64 ± 2.41 kΩ vs. 10.43 ± 2.69 kΩ, $p = 0.0251$) and after one year (9.97 ± 1.39 kΩ vs. 10.94 ± 1.11 kΩ, $p = 0.0061$). The robotic group also showed significantly lower stimulation thresholds and the most comfortable loudness (MCL) levels ($p < 0.0001$), indicating a more stable electrode–nerve interface [88].

While both studies support slower insertion, Rajan et al. isolate insertion speed as the sole variable, strengthening the claim that speed directly improves outcomes. In contrast, Sykopetrites et al. combine the effects of robotic precision and speed, making it harder to attribute benefits solely to insertion velocity. Rajan et al.'s controlled design and clinically

relevant data justify technologies like iotaSoft® SOFT, which deliver consistent slow insertions (0.2 mm/s) [85,89]. Such devices effectively optimize CI outcomes by minimizing mechanical trauma.

A major advancement in robotic-assisted CI is the reduction of electrode translocation rates, especially for lateral wall arrays, compared to manual methods [74,77]. Unlike manual insertions, which vary by technique and surgeon skill, robotic systems maintain stable insertion dynamics, reducing trauma to delicate cochlear structures. They also better navigate complex anatomies. For example, RobOtol® was successfully used in a 63-year-old patient with atypical middle ear anatomy via the pericanal approach [90].

A retrospective study of 60 cochlear implantations by Maheo et al. reinforced these findings. They compared 20 robotic and 40 manual insertions. Robotic insertions with RobOtol® showed fewer scalar translocations, 19% versus 31% in manual cases, and fewer translocated electrodes (7% vs. 16%, $p < 0.0001$) [71].

Slower insertion speeds are closely associated with a reduced likelihood of electrode translocation and play a critical role in preserving delicate intracochlear structures by minimizing trauma. This theoretical advantage is well-supported by empirical data from robotic cochlear implant (CI) systems such as RobOtol®, iotaSoft®, and OtoDrive®. These systems consistently outperform manual techniques in reducing insertion-related trauma and enhancing consistency, regardless of variations in design and methodology.

Multiple studies have consistently demonstrated that robotic systems outperform manual techniques in reducing insertion trauma and enhancing surgical precision. For instance, Torres et al. compared RobOtol®-assisted and manual insertions in 20 human temporal bones. They found that a controlled insertion speed of 0.25 mm/s along a cochlea-aligned trajectory resulted in significantly higher scala tympani placement rates ($p = 0.03$), lower trauma scores ($p = 0.04$), and deeper electrode insertions without increased trauma risk ($p < 0.001$) [60]. Similarly, Kaufmann et al. reported that iotaSoft® significantly reduced trauma scores in cadaveric cochleae (0.9 ± 1.0) compared to manual methods (3.1 ± 2.0) [73]. Claussen et al. further confirmed these benefits, demonstrating lower trauma scores with iotaSoft® robotic insertions (1.3 vs. 2.2; $p < 0.05$) [91]. Complementing these findings, Alhabib et al. showed that the OtoDrive® system maintained a significantly slower and more controlled insertion speed (0.1 mm/s versus 0.66 ± 0.31 mm/s) without compromising electrode placement or cochlear coverage [80].The results are depicted in Table 5.

Table 5. Insertion trauma results for robots.

Robot Name	Insertion Trauma (p)	Reference
RobOtol®	0.0055	[88]
iotaSoft®	0.9 ± 1.0 N	[73]
OtoDrive®	Not reported	[80]
Manual Insertion	0.04	[77]

Robotic-assisted cochlear implantation facilitates deeper insertions, more accurate electrode placement, and significantly reduces trauma compared to manual techniques. Conversely, manual insertion exposes patients to greater procedural variability and increased risk due to inconsistent force application and angle control. However, this improved precision incurs longer surgical times. Specifically, robotic procedures generally require substantially more time than manual methods.This raise concerns about prolonged anesthesia and associated patient risks [18,88]. While experienced surgeons complete manual cochlear implantation within approximately 80–90 min, robotic surgeries often extend anesthesia duration to 3–5 h, increasing the risk of complications [89].

Supporting this, studies of the RobOtol® system report longer insertion times for robotic electrode placement, averaging 197.8 ± 64.5 s compared to 72.8 ± 10.1 s for manual insertion [6,71]. Moreover, robotic setup adds an additional 4 ± 1 min before insertion. This underscores the trade-off between enhanced surgical accuracy and increased procedural time [71]. Table 4 summarizes insertion times across various robotic platforms, highlighting this balance between precision and efficiency.

Looking at the impact of CI on speech outcomes, robotic cochlear implantation (CI) has not consistently yielded improved results. Although some studies suggest that better preservation of residual hearing may enhance speech performance [92,93], the overall impact on long-term speech development remains inconclusive. For instance, Heuninck et al. (2023) conducted a long-term comparative study of HEARO®-implanted patients and found no significant audiological differences compared to conventional implant recipients, with outcomes closely mirroring traditional approaches [94]. Similarly, Maheo et al. reported comparable results using the RobOtol® system [71]. This review concludes that while robotic systems optimize electrode insertion speed and reduce trauma, auditory outcomes remain comparable to manual methods.

Although cochlear implants provide well-established clinical benefits, their widespread adoption is limited by high costs, especially for advanced technologies. Economic evaluations of robotic otological surgery remain scarce, creating uncertainty about its cost effectiveness [95]. For instance, a strategic simulation study in Germany projected a persistent undersupply of cochlear implants despite expanding indications, with annual costs estimated at EUR 538 million. These costs could increase to EUR 765 million as technology advances and patient acceptance grows, further burdening healthcare systems [96]. Similarly, a Canadian cost–utility analysis found that bilateral cochlear implantation offers greater benefits than unilateral implantation, with an incremental cost–utility ratio (ICUR) of CAD 14,658 per quality-adjusted life year (QALY) compared to no intervention, supporting its cost effectiveness. However, compared to unilateral implantation, the ICUR increased to CAD 55,020 per QALY and was sensitive to factors such as device cost, upgrades, and failure rates [97]. Collectively, these studies underscore the economic challenges and complexities involved in adopting advanced cochlear implant technologies.

The cost of robotic systems also increases due to reliance on advanced imaging techniques such as CT and CBCT. These imaging techniques increase both expenses and patient radiation exposure. Although these technologies enhance surgical precision, their cost effectiveness remains uncertain. Emerging intraoperative alternatives, such as electrocochleography (ECochG), offer real-time cochlear monitoring with potentially lower costs [98]. Additionally, artificial intelligence (AI) increasingly aids in predicting electrode insertion depth and trajectory [10,99,100], with systems like OtoDrive® uniquely applying AI to postoperative outcome assessment. The integration of AI and machine learning into robotic cochlear implant systems holds promise for reducing costs while improving workflow and clinical outcomes. Future developments should prioritize affordability and accessibility, particularly within publicly funded healthcare systems [74,80].

Therefore, this review highlights the growing role of monitoring and planning methods, especially those supported by artificial intelligence, in improving cochlear implant outcomes.

Expanding on economic and technological factors, common robotic CI platforms such as HEARO® and ROSA® often demand large operational spaces and encounter difficulties navigating the confined middle ear anatomy. Their designs may constrain surgical precision and adaptability. Conversely, parallel manipulators, including Vanderbilt's system and hexapod platforms, offer enhanced stability, accuracy, and dexterity within a smaller footprint. This improved maneuverability facilitates more precise navigation of intricate

middle ear structures, thereby reducing trauma risk [101]. Nonetheless, clinical integration of these robotic systems presents logistical challenges. Additional operating room space and specialized personnel are required, while surgeons must engage in continuous training to achieve proficiency, as current robots remain assistive rather than autonomous. Furthermore, workflow modifications are necessary to fully leverage robotic precision. Consequently, successful adoption depends on balancing technological benefits with practical considerations to optimize patient outcomes.

In summary, robot-assisted cochlear implantation markedly enhances surgical precision and consistency while reducing intracochlear trauma compared to manual techniques. Systems such as RobOtol®, iotaSoft®, and OtoDrive® offer superior control over insertion speed and trajectory, which leads to fewer scalar translocations and improved cochlear preservation, particularly in complex anatomies. Nonetheless, despite these benefits, evidence linking robotic implantation to improved long-term audiological outcomes remains inconclusive. Limitations including dependence on manual components, prolonged surgical durations, anesthesia-related risks, anatomical restrictions, and high costs impede widespread adoption.

While advanced imaging contributes to increased costs and radiation exposure, emerging AI-driven planning, real-time intraoperative monitoring, and compact robotic designs show promise in improving accessibility and efficiency. Future research must prioritize cost reduction, workflow optimization, and rigorous assessment of the impact of robotic cochlear implantation on auditory outcomes to facilitate its integration into routine clinical practice.

7. Conclusions

This review evaluates robotic systems developed for cochlear implantation, with a focus on middle ear access, direct cochlear access (DCA), and electrode insertion. The analysis encompasses mechanical design, clinical protocols, outcomes from in vitro and clinical studies, and overall system performance. Key metrics assessed include implant success rates, electrode translocation, cochlear trauma, hearing preservation, and speech recognition. Clinical evidence indicates that robotic systems offer significant advantages by reducing translocation rates and enabling slower, more controlled insertions, thereby preserving cochlear structures. However, these benefits are accompanied by longer surgical times, higher costs, and limited improvements in speech perception. Continued refinement of robotic platforms is necessary to address these limitations. Comparative evaluations of cost-effectiveness, procedural efficiency, and clinical applicability are critical to overcoming adoption barriers. As robotic cochlear implantation evolves, the primary goal remains to provide safer, more precise, and less traumatic procedures that improve auditory outcomes and quality of life for individuals with hearing loss.

Author Contributions: Conception, design, writing editing, data gathering and analysis: O.A.; Conceptualization, formal analysis: M.W. and B.Z.; Validation and conceptualization: R.I. and P.B. Project supervision, conceptualization, validation, formal analysis and funding acquisition: X.D. All authors have read and agreed to the published version of the manuscript.

Funding: Oneeba Ahmed's PhD is funded by the Royal National Institute of Deaf People (R.N.I.D) under grand number S64 to Brunel University of London, UB8 3PH, United Kingdom.

Data Availability Statement: No new data were generated or analyzed in this study; therefore, data sharing is not applicable.

Conflicts of Interest: The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

CIs	Cochlear Implants
DCA	Direct Cochlear Access
IGS	Image Guiding System
ST	Scala Tympani
EA	Electrode Array
AI	Artifical Intelligence
ML	Machine Learning

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