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Review Article

A Historical Review of Medical Robotic Platforms

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This paper provides a brief history of medical robotic systems. Since the first use of robots in medical procedures, there have been countless companies competing to developed robotic systems in hopes to dominate a field. Many companies have succeeded, and many have failed. This review paper shows the timeline history of some of the old and most successful medical robots and new robotic systems. As the patents of the most successful system, i.e., Da Vinci® Surgical System, have expired or are expiring soon, this paper can provide some insights for new designers and manufacturers to explore new opportunities in this field.

1. Introduction

Due to technological advancement, research and development of medical robots has revolutionized the way medical procedures take place, including surgical operations. This tremendous progress can be attributed not only to technological advancement, including actuators, sensors, control systems, and materials but also to the growth of imaging systems for medical applications such as higher resolutions and magnetic imaging [1]. Widespread acknowledgment of medical procedures that have been successfully performed with the aid of robotic systems has led to an increase in the number of individuals willing to undergo a procedure performed either solely by a robot semi-autonomously or a robot-assisted procedure. This in turn leads to the rapid advancement of the field of medical robotics.

Robots are generally defined as machines that can be programmed to perform a specified set of simple or complex tasks, with or without human assistance. One advantage of using robotic assistance is the capability to program for performing tasks that require high-speed motion with a focus on precision and accuracy. Robots may also perform tasks that require strength application without becoming worn out. Some of the disadvantages associated with the use of robotic systems include their high price, large space required to operate, need for frequent maintenance, and need for properly training operators such as doctors and clinical staff prior to use [2–4]. Despite these disadvantages, the positive impact of medical robotic systems can be observed in surgery, where the achievement of an acceptable improvement in precision and accuracy levels results in the enhancement of procedures such as tissue manipulation. Research and clinical studies have reported significant improvement in outcomes of surgical operations [5–7], including a reduction in trauma experienced by patients [3, 7, 8] and post-procedure recovery of patients [1, 9]. Some of the major fields of medicine have been greatly impacted by the introduction of robotic systems, such as the Renaissance® System introduced in 2011 [10], which has been proven to increase the accuracy rate by a factor of 85% to 100% [1, 2] and is extensively accepted for use in spinal surgeries [10]. MAKO, one of the leading robotic systems for orthopedic procedures, was launched in 2015 [11] and provides accuracy and precision that eliminates the need for manual instruments [3, 12]. The most widely known robotic system, the Da Vinci® Surgical System [5, 13], is primarily used for performing minimally invasive surgery (MIS). Being a "master-slave" system, the Da Vinci® platform helps surgeons perform tasks in which there is the possibility of failure to operate smoothly, through the use of advantageous features like the filtering of tremors

[1, 14, 15]. The systems mentioned above are discussed in further detail in the following sections.

Some of the most renowned medical robotic systems, such as the Da Vinci® Surgical System, have existed since the late 1990s [14]. As more than two decades have passed, most patents that were filed and granted have expired or are about to expire; therefore, the technology and methods provided in patents may be used by others to create systems with similar technologies. The design and development of similar systems create competition between companies, which may lead to improved quality of the systems and a reduction in costs.

Over the past three decades, various robotic platforms have been reviewed in various scientific or informative publications internationally. Some reviews focused on specific applications of robots and their systems, while others focused on robotic systems from a general standpoint [1]. Nevertheless, as mentioned, the field of robotics is evolving at a very fast pace, which creates a need to summarize these achievements every few years. In this review paper, the existing robotic platforms used in the field of medicine will be summarized, and an overview of informative efforts conducted by fellow researchers will be discussed. We hope that the current content will assist stakeholders in better understanding existing medical systems and identifying the available options for making an informed decision from design to industrialization. This paper categorizes the medical robotic system based on the time of development or introduction. Specifically, this paper studies three different decades of medical robotic systems history.

2. Medical Robotic Systems: A Review through Different Decades

2.1. Decade I: 1990–2000 (First Generations). The earliest record of the use of robots in a medical procedure dates to 1985 when an industrial robot was used to perform brain biopsy using the help of CT imaging and preprogramming of its movement. This project was discontinued due to the safety concerns with using an industrial robot to perform delicate procedures such as brain biopsy [1]. This milestone marked the start of a new era where robotic systems assist doctors and surgeons in performing medical procedures. Figure 1 shows the timeline of the development of robotic systems developed in decade I, from 1990 to 2000.

2.2. NeuroMate®. NeuroMate® is a robotic system designed to perform neurosurgery and was developed by Integrated Surgical Systems Inc., USA (it is currently owned by Renishaw plc, UK). NeuroMate® is one of the oldest running systems commercially available. By design, it has 6 Degrees of Freedom (DOFs) along with a stereotactic system, which enables it to perform various neurological procedures such as neuroendoscopy, deep brain stimulation, biopsy, transcranial magnetic stimulation, radiosurgery, and resection of brain tumors [1, 14, 16].

2.3. ROBODOC® Surgical System. ROBODOC® is a first of its kind surgical system designed to perform orthopedic procedures, specifically THA (Total Hip Arthroplasty), with later versions developed for TKA (Total Knee Arthroplasty) [3]. It was jointly developed by Integrated Surgical Systems Inc., USA, and IBM T.J. Watson Centre, USA. This technology was sold to Curexo Inc. in 2007, which later became Think Surgical, Inc. in 2014. Think Surgical is currently developing and selling newer versions of ROBODOC® under the brand name of TSolution One [17].

The ROBODOC® surgical system is divided into two parts; the first being ROBODOC®, which consists of a robotic arm for performing surgery, and the second being Orthodoc, which is a 3-D computer modelling station. The latter acts as an assistance system that helps in planning and executing the surgery by using presurgical images [3, 18]. This system enables the surgeons to precisely define the hip bone cavity, size, and position of the prosthesis during the planning stage of operation. The system is programmed to cut the patient automatically, increasing the precision and accuracy of the procedure as compared to normal methods of incision by the human hand, as ROBODOC® uses bone motion detectors fixed about 5 mm deep in the bone, which are not compromised by debris and fluids [14–16].

2.4. AESOP™ Robotic Surgical System. The AESOP™ (Automatic Endoscopic System for Optimal Positioning) Robotic Surgical System is also a first of its kind robotic system developed by Computer Motion Inc., USA, to assist in laparoscopic procedures. This project was partially funded by the Defense Advanced Research Projects Agency (DARPA). As the name suggests, AESOP™ is used to hold and move the endoscope to better assist the surgeon while operating. The first version, AESOP™ 1000, was positioned either by hand or pedal after being mounted on an operating table or nearby cart. The later version, AESOP™ 2000, was released in 1996 and became voice-activated [1, 8]. This system was comprised of two major technologies; the first being a robotic arm to control the placement of the endoscope and the second being a computer that recognizes voice commands. The computer held limited prerecorded voice commands from specific surgeons to control the robotic arm. AESOP™ was used to assist in minimally invasive surgeries in the field of urologic, thoracic, cardiac, and gastrointestinal surgeries [8, 17].

2.5. CyberKnife® System. The CyberKnife® Robotic Radiosurgery System was the first of its kind robotic system designed for stereotactic radiosurgery and body radiation therapy. This system was developed by Accuray Inc., USA. It is an image-guided frameless radiosurgery system [18].

The robotic manipulator (with 6-DOF) is used to mount a linear accelerator (LINAC), which is used for projecting high energy radiation over a wide range of different orientations; this allows the treatment to be carried out successfully with the least possible trauma to the patient [1]. The patient table, called RoboCouch, consists of 6-DOF and can deliver submillimetre precision while moving patients in the required direction and space. RoboCouch can position the patient with high accuracy [19] while compensating any of their movements (i.e., breathing and a slight change in

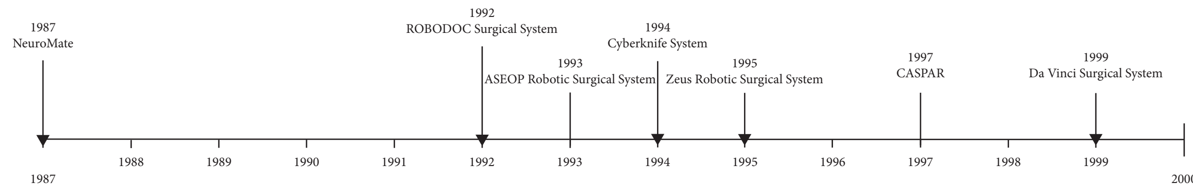


Figure 1: Decade I: timeline of robotic systems that founded and created the base for usage of robots in the medical field.

posture). Other components of this system include stereoscopic X-ray systems that create a free-breathing model of each patient and verify the position of the target during the procedure. To track the breathing of the patient, a Synchrony Respiratory Tracking System is used, which allows real-time tracking and enables the entire system to take corrective measures effectively [20]. Generally, the procedure takes roughly one and a half hours to complete but can vary based on the location and size of the tumour to be removed. This system can be used in various procedures, such as when treating catastrophic epilepsy caused by hypothalamic hamartoma [21], treating tumours located anywhere in the body [17, 19], and radiotherapy.

2.6. Zeus® Robotic Surgical System. The Zeus® Robotic Surgical System (ZRSS) was a ground-breaking system developed to perform laparoscopic procedures by Computer Motion Inc., USA. This system was created by adding two robotic arm manipulators with 4-DOF to the AESOP™ robotic system in 1995, thereby creating the first surgical system for use in minimally invasive surgeries. The movement of robotic arms was controlled by surgeons through a console, making it one of the first "master/slave" systems ever to be made. ZRSS helped improve the dexterity of surgeons and increased the safety of medical procedures, as it had an in-built feature that reduced hand tremors of the surgeon operating it [1].

On September 07, 2001, ZRSS made history as it was used to perform the first telesurgery over the Internet. During this transatlantic cholecystectomy procedure (known as the Lindbergh operation), the surgeon was located in New York, USA, and the patient in Strasbourg, France, with around 7000 km between them [8, 17]. Both Zeus® and AESOP™ were discontinued in 2003 when Intuitive Surgical Inc. acquired Computer Motion Inc.

2.7. CASPAR®. The CASPAR® (Computer-Assisted Surgical Planning and Robotics) system is a robotic system developed for hip and knee replacement surgeries by OrtoMaquet in Germany. Like the ROBODOC® system, this system is used primarily for the autonomous milling of bone and femurs in preparation for the procedure. This system has 6-DOF and contains an interactive computer system used for the planning of surgery based on data obtained from CT scans. CASPAR® has been used to perform total hip replacement and total knee replacement procedures [14, 22]. While this system had advantages, such as an increase in accuracy and alignment, its disadvantages were significant; these included an increase in blood loss and procedure time that gave rise to more complications [7]. CASPAR® was in direct competition with the ROBODOC® system and was discontinued in 2001 after Universal Robot Systems (URS) acquired it [1].

2.8. Da Vinci® Surgical System. The Da Vinci® Robotic Surgical System is one of the most widely used and renowned surgical systems in the world. This system was developed by Intuitive Surgical, USA, to perform minimally invasive surgical procedures. The Da Vinci® system was released after the Zeus® Robotic Surgical System had made its debut in the year 1995. It is widely known as and accepted to be one of the best surgical systems for minimally invasive procedures even today. There are three main components of this system: the surgeon's console, the patient's cart (which contains the robotic arms), and the vision cart (containing the housing monitor, recording equipment, etc.). The surgeon's console provides options for customization, such as changing the height, reach, and control of the robotic arms. The console also provides additional features for the filtering of tremors from the surgeon's hand along with 3-D HD vision of the operating site. The vision cart acts as a communication hub for the entire system, providing power generation, image processing, and housing the information system; it also contains a display screen that provides a live display of the operation site for individuals present in the operation room [8, 23].

The first-generation model of the Da Vinci® system consisted of three robotic arms (6-DOF and 1-DOF for the wrist). Later, in 2003, Intuitive Surgical introduced an additional arm for purchasing. The latest generation Da Vinci® system added another surgeon's console that provided an option for operating with two surgeons simultaneously [1, 8]. After the initial FDA approval, the Da Vinci® system has now gained FDA approval for numerous procedures including, but not limited to, applications in laparoscopies, urology, thoracoscopies, prostatectomies, pediatrics, cardiotomy, revascularization, gynecology, transoral otolaryngology, single-site cholecystectomies, and hysterectomies [1, 8, 17, 24].

A summary of all robotic systems pioneered the field of medical robots, developed in the 1990s, is provided in Table 1.

3. Decade II: 2000–2010 (Middle Generations)

Figure 2 shows the timeline of robotic systems developed in decade II from early 2000 to late 2010.

Table 1: Robotic systems that were developed during decade I, from 1990 to 2000 (first generations).

No	Robotic system	Company	Year	Regulatory status	Procedures
1	NeuroMate®	Currently–Renishaw plc, UK	1987	FDA–1997 (First model) CE mark–1997	Deep brain stimulation (DBS), stereoelectroence-phalography (SEEG) [1, 2, 11, 17]
2	ROBODOC® Surgical System	Current–Think Surgical, USA	1992	CE mark–1996 FDA–1998 (THA) FDA–2009 (TKA)	Total hip arthroplasty, Total knee arthroplasty [1, 7, 14, 15]
3	AESOP™ Robotic Surgical System	Computer Motion Inc., USA	1993	FDA–1994 (first model)	MIS–urologic, thoracic, cardiac, etc. fields [8, 17]
4	CyberKnife®	Accuray Inc, USA	1994	FDA–2001	Radiosurgery, SBRT, Hypothalamic hamartomas [1, 18, 19, 21]
5	Zeus® Robotic Surgical System	Computer Motion Inc., USA	1995	FDA–2001	MIS, cardiac procedures [1, 8]
6	CASPAR®	Orto-Manquet/U.R.S, Germany	1997	N/A	TKA, THA, anterior crucial ligament repair [1, 14, 22]
7	Da Vinci® Surgical System	Intuitive Surgical, USA	1999	FDA–2000 (first model)	MIS [1, 2, 4, 8, 24]

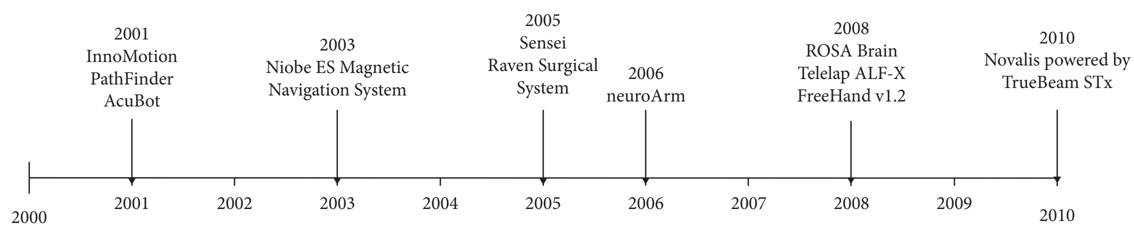


Figure 2: Decade II–timeline of robotic systems that signify the progress of the development curve of Robots in medical application.

3.1. AcuBot. AcuBot was developed by the URobotics Laboratory at John Hopkins University (USA) for percutaneous access procedures. This robotic system combines four robotic systems, namely, PAKY (Percutaneous Access of Kidney) and RCM (Remote Centre of Motion), along with an S-arm (mounted on the bridge) and XYZ Cartesian Stage (3-DOF), all developed by the same institute. The robotic manipulator, AbuBot's S-arm, has 7-DOF and uses a laser marker from CT-scans to guide and position the needle accurately for the procedure [25]. The robot has 6-DOF for decoupled positioning, orientation, and instrument insertion [26].

AcuBot was developed with the hope of replacing surgeons and other staff in the operating room during dangerous procedures that involve the use of fluoroscopy or CT imaging. This would help by reducing the radiation exposure of staff. AcuBot's structure—specifically the S-arm—provides sufficient free movement to the system and allows interventions to be performed anywhere on the body with various imaging modalities [25, 26].

3.2. PathFinder™. The PathFinder™ robotic system was developed by Armstrong Healthcare Ltd., UK, for use in neurological applications. This is the first robot developed in its field for image-guided surgeries. PathFinder™ is a stereotactic system using a 6-DOF arm, with a camera (micro head CCD) mounted on the final axis of the arm. Key features that differentiate PathFinder™ include a camera that is used to find the surgical site instead of traditional means like radiological, ultrasound, or mechanical methods [2, 27, 28]. PathFinder™ also has an operation capability of submillimetre accuracy, which helps in guiding the needle during biopsies [1, 2]. In addition to PathFinder™ robotic system, some general industrial robots were used for ultrasound scan application while remotely controlled. A study was conducted using Kuka robot in which a low-cost ultrasound equipment was employed to test some tasks on an artificial human body in order to validate the performance of a new, yet simple, control scheme [29]. This work was extended in [30].

3.3. InnoMotion. InnoMotion was developed by Innomedic GmbH, Germany, for use in percutaneous procedures. InnoMotion became the first robotic system used for these types of procedures along with AcuBot. The aim behind the development of this system was to create a system that is compatible and operable with MRI, providing accurate and reproducible instrument positioning within the magnetic field. The system consists of a robotic arm that is attached to a ring (260°), made of glass fiber-reinforced polyester, which is then mounted on an MRI patient's table. The arm has 6-DOF, with additional DOF that allows the system to change its position passively (0°, 30°, or 60° to perpendicular) depending on the operating site [25, 31]. The drawback of this system is that it is mounted on the patient table, which limits its flexible movement for selecting an entry point, as opposed to single-arm systems such as AcuBot [32].

3.4. Niobe™ ES Magnetic Navigation System. The Niobe™ ES Magnetic Navigation System was designed by Stereotaxis Inc. (USA) for use in catheter interventions. This system controls and maneuvers the catheter with the use of an electromagnetic field, and consists of four separate technologies: the Genesis Robotic Magnetic Navigation System® (RMN), the Imaging model S®, the Odyssey Vision System®, and the Vdrive® Robotic Navigation System. Genesis RMN contains two robot-controlled permanent magnets that are placed on either side of the patient table [33]. During the procedure, the magnets are used to produce the required magnetic field that is then controlled and manipulated by the surgeon/physician through a computer interface, thereby controlling the movements of the catheter, which has a magnet embedded in its tip. The Imaging model S® is an X-ray system developed for electrophysiology (EP); its key feature is a flat planar detector that reduces radiation and provides high-quality images. The imaging model S can also modulate its frame rate and has variable source-to-image distance (SID). The Odyssey Vision System was built specifically to integrate various systems required in electrophysiology (EP) labs into a single system, consisting of a mouse, keyboard, and monitor. The Vdrive Robotic Navigation System, along with Genesis RMN, provides stability and navigation for diagnosing and delivering improved ablation [34, 35]. Currently, this system has been successfully used in vascular and cardiac procedures, while making ablation procedures safer and easier to perform [35].

3.5. Raven Surgical System. The Raven Surgical System was designed to perform MIS procedures and open surgeries. Initially, this system was jointly developed by Blake Hannaford of the University of Washington (BioRobotics Laboratory) and Jacob Rosen of UC Santa Cruz (Bionics Lab) as a part of the DARPA project. Unlike the Da Vinci® system, Raven only has two robotic arm manipulators. Each arm has 6-DOF + 1-DOF (for grasp), for a total of 7-DOF. This system can be broken down into three parts: the patient's site (houses two robotic arm manipulators), the surgeon's site (houses two control devices and a live video feed of the operation site), and a network (any form of TCP/IP or other networks) connecting them [36], as in typical master/slave systems.

The later version of this system is known as Raven-II, which was designed as a platform for collaborative research and currently has seven different universities across the USA participating in it [37]. The Raven-II was designed to compensate for shortfalls of the Raven-I, incorporating arms that can be placed on either side of the surgical site and up to four arms (rather than two) that can be used to operate together on a single site. The greatest advantage of the Raven-II system is that it is an open-source system and can be bought for research for only $298K [17].

3.6. Sensei®. Sensei® is a robotic navigation system designed by Hansen Medical Inc., USA, for catheter interventions. This system consists of three main parts: a workstation, a manipulator, and a steerable catheter. Sensei's manipulator is electromechanical and is controlled by a computerized master. The later generation of the Sensei® robotic navigation system, i.e., Sensei® X, has an Artisan Extended catheter, which improves the performance, flexibility, and bends the radius of a catheter. The catheter inside the manipulator has a range of motion in 3-Dimensional (3-D) space, and another key feature is that the manipulator can have multiple catheters inside its guide catheter [24]. The movement of the catheter is controlled by a 3-D joystick at the workstation. Another distinct feature of the system is force measurement at the distal tip, which is then transmitted to an operator via a joystick in the form of vibrations. Furthermore, the workstation is equipped with multiple monitors that provide the surgeon with a wide array of information including ICE, fluoroscopy, 3-D mapping, and EKG reading. Some drawbacks of the system include a lengthy set-up time, huge size, and high costs [1, 24].

Despite this, Sensei® can be used for catheter ablation in atrial fibrillation, cardiac mapping, and endovascular aneurism repair. A study by Faizal Logart et al. revealed that Sensei® X offers a safe and effective approach for the treatment of atrial fibrillation [24, 38].

3.7. neuroArm™. The neuroArm™ Robotic system was designed for neurosurgery by the University of Calgary in Canada. This is a first of its kind robotic system, as it was the first telesurgery system that was fully compatible with MRI. neuroArm™ consists of two robotic manipulators (7-DOF; 6-DOF + 1-DOF tool actuator) and a workstation. The manipulators are designed to handle microsurgical tools. The workstation is ergonomically designed for longer duration procedures, equipped with an interface that provides both images from MR and live 3-D HD images from the operation site simultaneously [5, 6].

neuroArm™ is packed with features to assist the surgeon in various ways; these features include haptic feedback via a haptic hand-controller to the surgeon's hand, electronic tremor filtration, motion-scaling (Range—1 : 1 to 1 : 20), force-scaling (Range—1 : 1 to 1 : 20), and Z-lock. The latter feature enables the system to move in only one single direction while ignoring whether the surgeon's hand moves in a straight line or not, improving its target accuracy [5, 6, 39].

neuroArm™ assets were bought by IMRIS Inc. (Canada) in 2010, which later launched the modified and rebranded SYMBIS Surgical System in 2011.

3.8. FreeHand® v1.2. FreeHand® v1.2 is a robot designed by FreeHand® 2010 Ltd., UK, to control the camera during laparoscopic procedures. FreeHand® is a second-generation endoscopic camera holder developed from EndoAssist by Prosurgics, UK. The robotic system consists of seven parts: an electronic control box (power supply, electronics, and clamp), a lockable articulating arm (robotic motion system and speed control panel), a hands-free control unit (a headset to be mounted on the surgeon), an indicator unit (display direction of the camera), a foot pedal (controlling motion of the camera), a sterile zoom module (a single-use pack containing a motor with a zoom function and a place to hold the camera attached to a robotic arm), and a sterile sleeve to cover the arm and control box [40]. One advantage of this system lies in the ability to attach it to the patient table anywhere along the rail, depending on the place of the operation site. This system is designed to provide steady images of the operating site. The direction of motion is set through the headset on the surgeon's head, and it contains an infrared transmitter that transmits a signal to the monitor placed in line-of-sight. When the direction is selected, the indicator unit displays the direction in the form of arrows. The motion of the robotic arm is controlled by the surgeon through the foot pedal, which can move in three axes (pan, tilt, and zoom). This allows the surgeon to operate without any interruptions. In addition, the headset can be transferred between surgeons without the need to be reconfigured, which enables multiple users during a single operation [24, 41].

3.9. Telelap ALF-X. Telelap ALF-X is a surgical robot designed for the purposes of general surgery by SOFAR S.p.A, Italy, along with the Joint Research Centre (European Commission) in Italy. It is currently owned by TransEnterix Surgical Inc., USA. The system is comprised of three parts, including a console unit (called the surgical cockpit), three or four robotic arms (6-DOF each), and a connection node. The surgical cockpit is designed ergonomically, providing a view of the entire operating room, and like the Da Vinci® Surgical system, a second console can be added if need be. Unlike the Da Vinci® arm base, Telelap's manipulators are roughly 80 cm away from the patient table, allowing space for free movement of a nurse if desired. The arm can easily be moved into the required position as per the surgeon's or procedures need. Besides, all of the surgical tools are attached with arms with the help of magnets and therefore can easily be altered during the procedure. Another key feature of Telelap ALF-X is the eye-tracking system, an infrared-based system that tracks the movement of the surgeon's eye and shifts the endoscopic view to ensure that the point the surgeon is viewing is at the focus of the screen. Other features include haptic feedback, motion scaling, and reusability of tools [42, 43].

3.10. Novalis® Powered by TrueBeam™ STx. Novalis®, powered by TrueBeam™ STx, is a robotic system designed for performing radio surgeries. Novalis® combines two individual systems, namely, Novalis® Radiosurgery (launched in 2007 and developed by BrainLab Inc., Germany) and the TrueBeam™ STx system (launched in 2010 and developed by Varian Medical Systems, USA). The system consists of four parts: the Novalis® Radiosurgery platform, iPlan (for the planning of the procedure); ExacTrac (an X-ray imaging system provided by BrainLab Inc.); TrueBeam™ STx (an advanced linear accelerator); and HD120 MLC Multileaf collimator (for the shaping of high radiation high-resolution beams) provided by Varian Medical Systems, along with a patient table (6-DOF) similar to CyberKnife® [44]. The difference between Novalis® and CyberKnife® lies in the radiation source; CyberKnife's radiation source has higher DOF, but the Novalis® system can shape the radiation beam, claiming that this reduces the radiation outside of the field of operation [1]. This system can be used to perform the following procedures, among others: IMRT (intensity modulated radiotherapy), SRS (stereotactic radiosurgery), hypofractionated radiotherapy, and IGRT (image-guided radiotherapy) [45].

Table 2 provides information on medical robotic systems developed in decade 2000–2010.

4. Decade III: 2010–Present (New Generations)

Figure 3 shows the timeline of robotic systems recently developed in decade III from 2010 to the present time.

4.1. Renaissance®. Renaissance® is a robotic surgical guidance system designed for spinal procedures by Mazor Robotics, Israel. Medtronic Plc., Ireland, acquired by Mazor Robotics in 2016 in a 3-stage process completed in 2018. Based on SpineAssist, the primary function of Renaissance® is the planning of procedures using CT images and the guiding of the tool during a procedure. The software generates a 3-D image of the spine, whereby the surgeon decides on the implant positions. Renaissance® can be directly mounted on the patient's spine during the procedure, increasing the stability of the system while providing minimal discrepancy between the patient and the robotic system. It is also MRI-compatible, allowing the mechanical guide to be programmed and automated based on the trajectory defined with the help of MRI and CT scans, to plan the drilling of a keyhole, probe, needle insertion, etc. [1, 4, 17, 47, 48].

4.2. ROSA ONE®. ROSA® (Robotic Stereotactic Assistance) ONE was designed by Zimmer Biomet Robotics (formerly Medtech SA), France, to perform brain and spinal surgeries. ROSA ONE® combines the technology of two previous surgical robots—ROSA® Brain and ROSA® Spine—both used in neurosurgeries and spinal surgeries, respectively. ROSA ONE® obtained the CE mark in 2016 for both brain and spine applications and received FDA approval for brain, spine, and knee applications in 2019, making ROSA ONE® the first robotic platform to receive both clearances. This system consists of a monitor and robotic arm manipulator attached to a single body. The robotic arm has 6-DOF for flexibility and dexterity while accessing the operation site. Other features of this system include multiple registrations and head fixations to improve surgeon workflow, and haptic technology that acts as an interface between the surgeon and the system [4, 46, 49].

4.3. Flex® Robotic System. The Flex® Robotic System was designed by Medrobotics Corp., USA, for providing robot-assisted visualization during general surgeries and minimally invasive procedures. The system consists of three parts: Flex console, Flex cart (housing the Flex base and Flex scope), and single-use Flex instruments. The system has two guide tubes attached to provide tactile feedback and various

Table 2: Robotic systems that were impactful during decade II, from 2000 to 2010 (middle generations).

No	Robotic system	Company	Year	Regulatory status	Procedures
1	AcuBot	Urobotics Lab, USA	2001	NA	Percutaneous access, radiological percutaneous interventions [25, 26]
2	PathFinder™	Current–Prosurgics, UK	2001	FDA–2004	Stereotactic neurosurgery, brain tumors, Parkinson's disease, and epilepsy [27, 28]
3	InnoMotion	Current–DePuy Synthesis Inc., USA	Initial model–2001	CE mark 2005	MRI-guided percutaneous interventions [25, 31, 32]
4	Niobe™ ES Magnetic Navigation System	Stereotaxis, USA	2003	CE mark–2008 FDA–2009	Treatment of cardiac arrhythmias, catheter interventions, endoscopy [33, 35]
5	Raven Surgical System	Universities of Washington and California, USA	2005	NA	MIS [36, 37]
6	Sensei®	Current–Auris Health, USA	Initial Experiment–2005	FDA–2007	Catheter interventions, atrial fibrillation [33, 38]
7	NeuroArm™	Current–IMRIS Inc., Canada	2006	FDA–2008	Microsurgery, stereotaxy, neurosurgery, treatment of glioma, [2, 5, 6, 39]
8	FreeHand® v1.2	Free hand 2010 ltd, UK	2008	FDA–2009	Laparoscopy, MIS [1, 24]
9	Telelap ALF-X	Current–TransEtrix Surgical Inc., USA	2008	CE mark–2011	Gynecological surgery [42], endoscopy, [43]
10	ROSA® Brain	Zimmer Biomet, France	2008	CE mark–2008 (from website) FDA–2012	Keyhole procedures, open skull operations, deep brain stimulation [1, 3, 4, 46]
11	Novalis® powered by TrueBeam™ STx	BrainLab Inc., Germany and Varian Medical System, USA	2010	NA	Radiosurgery, radiotherapy [1, 45]

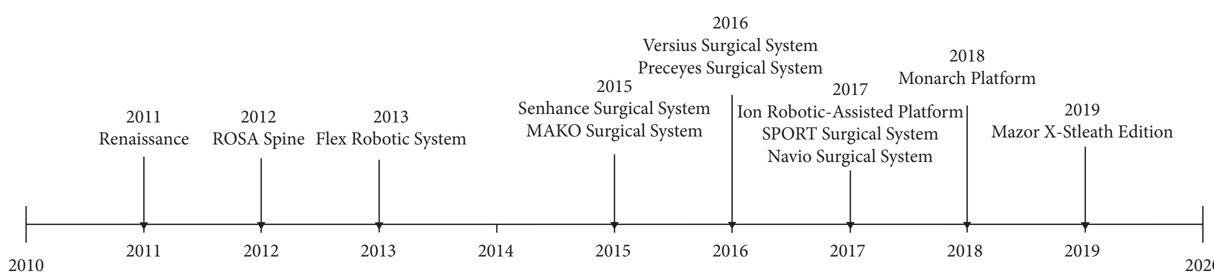


Figure 3: Decade III–timeline of robotic systems that show the recent advancement in the field of medical robots based on the advancement of technology and effort of three decades of research in this field.

incision tools. The movement of the scope is controlled by the surgeon via a console, where a joystick controller and an HD monitor (touch screen) are held. The flexible tube-like structure of the scope allows it to be maneuvered towards hard-to-reach places more so than with a rigid scope, as it can circularly move 180°. Another advantage of the Flex® Robotic system is that it contains integrated lens washers to help keep the camera clean [24, 50, 51].

4.4. MAKO™ Surgical System. The MAKO™ Surgical System was developed by MAKO™ Surgical Corp. (acquired by Stryker Corp. in 2013) and is based on the RIO® (Robotic Arm Interactive Orthopaedic) System. The RIO system gained FDA approval in 2008 for Total Knee Arthroplasty (TKA) and in 2010 for Total Hip Arthroplasty (THA). Stryker Corp. further developed the RIO system and rebranded it under the name MAKO, launching it again in 2015. Similar to its predecessor, the MAKO™ system is an orthopedic assistance system for procedures such as THA and TKA. MAKO™ can also be used for Unicompartmental Knee Arthroplasty. Operations with the MAKO™ system start with a CT scan, which is used to create a 3-D image of the operation site, i.e., the patient's knee/hip. The surgeon then virtually templates the components in the optimal position. Another advantage of the MAKO™ system is AccuStop, a haptic technology that is used to provide feedback (auditory beep, visual colour changes on the screen, and tactile vibrations) to surgeons. This technology guides the surgeon while making incisions, saving soft tissues and healthy bones in patients [52]. The MAKO™ system has been proven to increase accuracy in procedures and reduce recovery time and morphine consumption. Drawbacks of the MAKO™ system include its high purchasing cost (and corresponding surgery costs) along with increased exposure to radiation (from CT scans) [15, 53].

4.5. Senhance™ Surgical System. The Senhance™ Surgical System was designed based on the Telelap ALF-X system for the purpose of MIS and laparoscopy. Senhance™ was developed by TransEtrix Surgical Inc., USA, to be a later generation of the ALF-X system, with the aim to provide compaction of the Da Vinci® Surgical System. Senhance™ consists of four parts: a control console called a cockpit (with a 3-D HD monitor, eye-tracking system, and foot pedals), up to four robotic arm manipulators (7- DOF), a connection node (connecting the arms to the console), and reusable instruments [54]. There are distinct features of Senhance™ that can be used as points of reference for comparison; for example, the robotic arms are individual and can be placed at a certain distance from the operating table (similar to the ALF-X system), while in the Da Vinci® system, all arms are mounted on the patient's cart. The eye-tracking system centers what the surgeon's eyes are focusing on, while the Da Vinci® system has a binocular view controlled by foot pedals. Another beneficial feature of Senhance™ is tactile haptic feedback that is provided directly to the surgeon's operating console [24, 55].

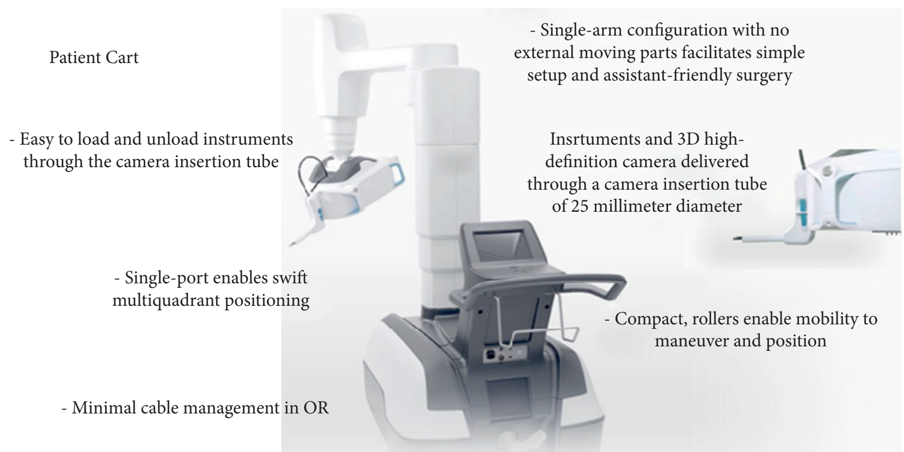
4.6. Preceyes Surgical System. The Preceyes Surgical System is a novel system designed by Preceyes BV, Netherlands, for the purpose of providing robotic assistance during eye surgeries. Preceyes aid surgeons in manipulating tools inside the eye. The system is designed to be similar to intraocular instruments, and therefore it does not change the way in which the procedure is conducted. Preceyes contains an instrument-integrated optical coherence tomography (OCT) A-scan sensor at the tip of an instrument that is used to specify the boundary of the operation site (which the instrument cannot exceed). Other features include auditory feedback, in case the instrument closes in towards the retina, a retraction mechanism (instant removal of the tool in case of an emergency), motion scaling (set differently for each procedure), and filtering of hand tremors. One of the greatest advantages of Preceyes is a high precision level of greater than 20 μm for holding and positioning instruments. Another function that this system provides is the recording of the entire procedure for post-op review and future training purposes [56].

4.7. Versius® Surgical System. The Versius® Surgical System was designed for Minimal Access Surgery (MAS) by CMR Surgical, UK. This system was designed to provide competition to Intuitive Surgical's Da Vinci® system. Versius® consists of a surgeons console (with 3-D HD display, and a controller for the bedside unit or BSU), four or five Versius BSUs divided into two parts (visualization BSU and instrument BSU), and a Versius endoscope, instruments, and cables (connecting the BSU to the console). The BSU is a standalone structure that acts as a movable station for the robotic arm (7–DOF), and they are designed in this fashion to increase the mobility of the entire surgical system from one operating room to another. One of the BSUs is mounted with an endoscope, and the visualization BSU and other BSUs (up to four) are used for housing instruments for operation. The console displays live 3-D images from the endoscope, and the surgeon has the option of operating either while sitting or standing based on preference or the nature of the procedure; this type of console increases the ease of view and enhances communication between the surgeon and his or her team. In addition, a 2-D feed is provided by an auxiliary display for other surgeons or nurses in the operating room [57, 58]. The Versius® surgical system is shown in Figure 4.

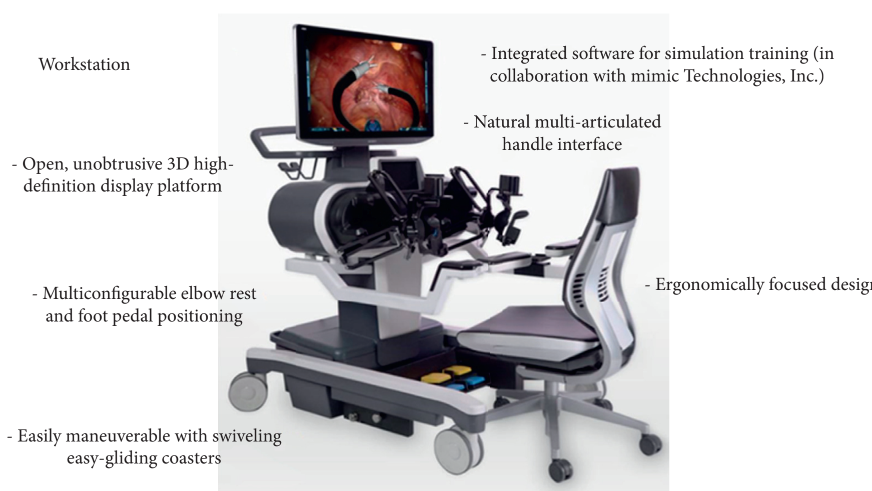
4.8. Navio™ Surgical System. The Navio™ Surgical System was designed for orthopedic procedures related to total and partial knee arthroplasty as well as unicompartmental knee arthroplasty. This system was created by Smith and Nephew Plc., UK, and based on Navio™ PFS, which gained FDA approval and the CE mark in 2012 and was acquired by Blue Belt Technologies, USA, in 2015. The Navio™ system consists of a computer, a monitor, and a handheld device. Navio™'s handheld tool provides the surgeon with a 6-DOF of movement. Unlike previous surgical systems used for the same application, Navio™ does not use CT scans in the planning of the procedure; rather, all planning is conducted intraoperatively. With this method, atomic landmarks and surface painting techniques are used to create a 3-D model of the patient's anatomy, which helps to determine the workflow. This eliminates the patient's exposure to radiation from CT scanning. One of the advantages of Navio™ lies in its handpiece, which is semiautomatic, i.e., if the surgeon deviates from the defined incision path, the drill tip retracts inside of the device and halts any unnecessary incisions [7, 59]. After the acquisition of BrainLab's orthopedic division in 2019, the Navio™ Surgical System underwent a software upgrade to Navio™ 7.0. This software upgrade added several advantages including a 72% reduction in required data point collection, a 40% reduction in workflow stages, improved usability, and faster image-free mapping and surface modelling [60].

4.9. SPORT™ Surgical System. The SPORT™ (Single Port Orifice Robotic Technology) Surgical System was designed for single-incision laparoscopic procedures by Titan Medical Inc., Canada. The system consists of a surgeon workstation (3-D HD monitor and controller), a patient's cart (single support suspending control unit), and specialized instruments (single-use replaceable tip). The workstation is designed in an open ergonomic format that can be adjusted depending on the surgeon's preference; this improves direct communication with other staff in the operating room. The control unit (CU) is suspended near the patient's table at a fixed position. On the CU, a 25 mm diameter camera insertion tube (CIT) is attached. The CIT carries two multi-articulated instruments with replaceable single-use tips and a 3-D HD camera with a light source. For single-incision procedures, the CIT enters the patient's body through a single 25 mm diameter incision [24, 61]. The SPORT™ surgical system is shown in Figure 5.

Figure 4: Versius® Surgical System; Copyright CMR Surgical Ltd. Surgeon console (left) with a monitor mounted on it; bed side unit (Right), manipulated with help of console.



(a)



(b)

Figure 5: SPORT™, Titan Medical Robotic Surgical System; (a) Patient's cart; (b) surgeons workstation; Copyright Titan Medical Inc.

4.10. Ion™ Robotic-Assisted Platform. The Ion™ Robotic-Assisted Platform was designed by Intuitive Surgical Inc., USA, for minimally invasive biopsy and bronchoscopy procedures. The system consists of a single console, which houses the catheter, its controller, and HD monitors for visualization. The catheter is designed to be flexible and as thin as possible, with a 3.5 mm outer diameter and a 2.0 mm inner working channel. The maneuverability of this catheter is high, with a 180° articulation in any direction. In addition, the catheter is controlled by a ball-shaped controller, which allows the operator to change the direction of the catheter freely. The needle attached to the tip of the catheter, known as the Flexision Needle, is a specialized tool; it is flexible in nature and bends according to the position. Biopsy

Table 3: Robotic systems that were developed in Decade III, from 2010 to 2020 (new generations).

No	Robotic system	Company	Year	Regulatory status	Procedures
1	Renaissance®	Current Medtronic, Ireland	2011	FDA and CE mark 2011, FDA–2012 (neuro procedure)	Biopsies, osteotomies, spinal deformities [1, 3, 4]
2	ROSA® spine	Zimmer Biomet, France	2012	FDA–2016 CE mark–2014 (from website)	Biopsies, planning, [3, 4, 17, 46]
3	Flex® robotic system	Medrobotics Corp., USA	2013	CE mark–2014 FDA–2015 (ENT), 2017 (colorectal surgery)	Laparoendoscopic single-port surgery (LESS), transoral surgery [24, 50, 51, 65]
4	MAKO™	Stryker	2015	FDA–2015 (TKA), 2015 (THA)	Total Hip arthroplasty, Total knee arthroplasty, unicompartmental knee arthroplasty [15, 53]
5	Senhance™ Surgical System	TransEtrix Surgical Inc., USA	2015	FDA–2017	Laparoscopy, gynecological procedures, hysterectomy [24, 54, 55]
6	Preceyes Surgical System	Preceyes BV, Netherlands	2016	CE mark–2019	Retina surgery, intraocular procedures [56]
7	Versius® Surgical System	CMR Surgical, UK	2016 (cadaveric trials) reveal–2018	CE mark–2019	Minimal access surgery, colorectal procedures [57, 58, 65]
8	Navio™ Surgical System	Current–Smith and Nephew, UK	2017	FDA–2016 (TKR)	Knee prosthesis positioning, unicompartmental knee arthroplasty [59]
9	SPORT™ Surgical System	Titan Medical Inc., Canada	2017	FDA–to be applied in 2020	MIS, single-incision laparoscopic surgery (SIL), LESS [17, 24, 61, 65]
10	Ion™ robotic-assisted platform	Intuitive surgical, USA	2017	FDA–2019	Minimal invasive biopsy, MIS
11	Monarch™ Platform	Aruis Health, USA	2018	FDA–2018	Peripheral bronchoscopy, endoscopy, [63]
12	Mazor X–Stealth™ Edition	Medtronic Plc., Ireland	2019	FDA–2018	Spine surgery, Pedicle Instrumentation, MIS [46, 47]

procedures start with PlanPoint software that generates a 3-D model of the patient's airway (i.e., tree-like structure) based on input from CT scan. This model is used to identify targets and preplan a path of motion. This is then loaded onto the controller for use during the procedure [62].

4.11. Monarch™ Platform. The Monarch™ Platform was designed by Auris Health Inc., USA, for diagnostic and therapeutic bronchoscopy procedures. The Monarch™ Platform has high mobility due to its design, consisting of only a flexible robotic endoscope and platform (controller, monitor, and storage). The controller itself is designed in the form of a handheld gaming device, which makes it easy for the operator to manipulate the robot, even in small areas of the bronchial tree. The images and video are transmitted from the endoscopic camera to the platform in high definition. The advantage of the Monarch™ Platform over traditional methods in endoscopic procedures is that surgeons have clear, high definition visuals during the procedure. It should be noted that there is limited knowledge on the Monarch™ Platform due to the lack of information made public [63].

4.12. Mazor X–Stealth™ Edition. The Mazor X–Stealth™ Edition was designed as a guidance system for spinal procedures. This robotic platform is a combination of two previously existing platforms, Mazor X™ (launched in 2016 and developed by Mazor Robotics, now Medtronic plc.) and the Stealth system (developed by Medtronic Plc., Ireland). The platform consists of a workstation (with a touch screen control panel, system hardware components, and storage for the robotic guidance system), the robotic guidance system (a table-mounted robotic arm, surgeon control panel, and navigation camera), and specialized instruments [63]. Mazor X–Stealth™ Edition has options for preplanning (using CT images) and intraplanning (using an O-arm system), making it one of the rare systems that contain both robotic and navigation systems. The system was formed by incorporating stealth software into the Mazor X platform. The key features of Mazor X–Stealth™ Edition include real-time image guidance and navigation information through the use of interactive 3-D planning and an information system to deliver workflow predictability and flexibility. It also provides instrument tracking for the navigation of tools and prosthetics [47, 48, 64]. Table 3 provides a summary of robotic systems that were developed in decade III, from 2010 to 2020 (new generations).

5. Discussions

The field of robotics is constantly evolving alongside the rapid advancement of technology. Despite this, the application of robots in medicine only emerged within the last three decades, and therefore it remains an unexplored area. Many robotic systems are currently available and used in medical procedures, but not enough data exist on these systems yet. Regardless, it is evident that the introduction of robotic systems to the medical field has significantly impacted the entire industry of medical instruments and robots, along with the methods of medical procedures [66].

Most, if not all, currently available robotic systems only function as robotic assistance during medical procedures, acting as a guiding mechanism or safety net for patients by providing additional features (such as filtering hand movements or force-scaling); however, fully automated robotic surgery is not yet possible. In the future, robotic systems operated by Artificial Intelligence may exist that can perform surgery without the need for surgeons being present or having a supervisory role. One such example is Robot Xiaoyi, developed by Tsinghua University in China, which scored 456/600 on China's Medical Licensing Exam (passing criteria—360/600) in 2017 [1, 24].

It can be said that medical robotic systems have three core technologies that decide the utility and advantages of a given system: imaging technology, navigation technology, and assisting system. As seen in new systems such as the Monarch™ Platform and Ion Robot-Assisted Platform, improving the imaging technology will provide a significant benefit to currently available robotic systems, as this technology enhances the accuracy and registration points during procedures [48].

A point to consider is that with the advancement in various medical and technological fields, such as in gene therapy and nanorobotics, the mode of treatment may undergo drastic changes. We strive to make methods of treatment as easy and efficient as possible. In the future, there may be the development of nanotechnology that could render current medical robotic systems obsolete.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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