Innovative Medical Devices

Series Editors: Guang-Zhong Yang · Yubo Fan

Yao Guo
Giulio Dagnino
Guang-Zhong Yang

Medical Robotics

History, Challenges, and Future Directions

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Innovative Medical Devices

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Yao Guo • Giulio Dagnino
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Preface

Medical robotics for surgery, personalized rehabilitation, hospital automation, and high-throughput screening represents an important area of growth globally. Driven by increasing clinical emphases on improved surveillance and earlier diagnosis, it is moving into an era of precision intervention, demanding improved quality, minimally invasive access, and an unprecedented level of accuracy. The commercial success of the early-generation medical robots has inspired an ever-increasing number of platforms from both commercial and research organizations, resulting in more agile and intelligent systems. This book looks back through the last decades at how medical robotics has evolved into a major area of innovation and development involving integrated multidisciplinary collaborative effort. With improved safety, efficacy, and reduced costs, robotic platforms will soon approach a tipping point, moving beyond early adopters to become mainstream clinical practice, also defining the future of smart hospitals and home-based patient care.

This book is intended as an introductory literature by outlining the global trends and new research directions in medical robotics, highlighting associated technical, commercial, regulatory, and economic challenges. In particular, this book focuses on three areas of medical robotics: (1) robotic surgery (Chaps. 2 and 3), (2) rehabilitation robotics (Chaps. 4 and 5), and (3) hospital automation (Chap. 6). For each subject area, important clinical needs and technical aspects are discussed, focusing on practical systems and research publications that have contributed to key advances in medical robotics in recent years. Open challenges and future opportunities are identified and discussed in Chap. 7.

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Shanghai, China — Guang-Zhong Yang
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Yao Guo, Giulio Dagnino, and Guang-Zhong Yang

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Introduction

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"*Medical robotics is a rapidly advancing area of development, spearheading the evolution of precision medicine, personalized rehabilitation, and hospital automation. The commercial success of the early-generation medical robotic systems has inspired an ever-increasing number of platforms from both commercial and research organizations, resulting in smaller, safer, and smarter devices for general clinical use*." Medical robots include surgical robotics, rehabilitation and assistive robotics, and hospital automation robotics, as shown in Fig. 1.1. This book looks back through the last decades at how medical robotics has evolved into a major area of innovation and development. With improved safety, efficacy, and reduced costs, robotic platforms will soon approach a tipping point, moving beyond early adopters to become part of the mainstream clinical practice, defining the future of smart hospitals and home-based patient care. These platforms will also have a greater focus on early intervention and quality of life after treatment. This book outlines the global trends and new research directions of medical robotics, highlighting associated technical, commercial, regulatory, and economic challenges.

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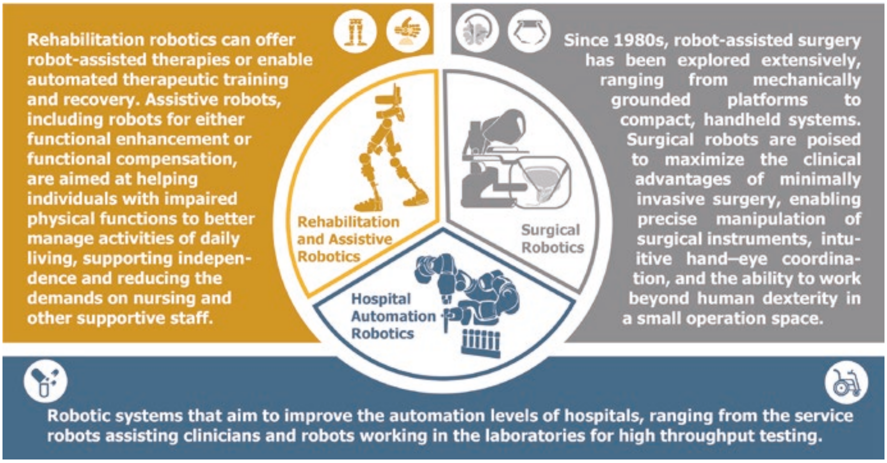

Fig. 1.1 Taxonomy of medical robotics. Medical robotics can be categorized into surgical robotics, rehabilitation and assistive robotics, and hospital automation robotics

1.1 Rise of Surgical Robotics

Since the end of the 1960s, when Driller and Neumann published the very first medical robot-related paper [1], the field of medical robotics has been in constant development. However, it was only in the mid-1980s that the concept of Health and Service Robotics was introduced, when the United States Congress was urged to support "*innovative research in functional rehabilitation of cognitive capabilities, speech, mobility, and manipulation*." During that period, robots in medicine were considered mainly as rehabilitation devices and nursing assistants [2]. In 1985, a conventional industrial robot, the Puma 200 (Unimation Inc., Danbury, CT) [3], was experimentally employed in a surgical procedure of needle insertion, demonstrating the first example of a surgical robot in history. Since then, an ever-increasing number of platforms from both commercial and research organizations have been developed and successfully used in a wide range of surgical specializations, such as neurosurgery, *Ear-Nose-Throat* (ENT), orthopedics, laparoscopy, and endoluminal intervention [2, 4–12].

Figure 1.2 shows the timeline of surgical robots, showing some of the platforms that have marked the last 30 years of surgical robotics development. The first generation of surgical robots relates to stereotaxic interventions in neurosurgery and orthopedics. For example, the Neuromate system (Renishaw, New Mills, UK) allows accurate neurological tool positioning procedures [14] (e.g., for biopsy, neuroendoscopy, and electrode implantation) using a robotic tool handler. ROBODOC (Curexo Technology, Fremont, CA) was the first surgical robotic system for orthopedics (i.e., hip replacement) that reached the market in 1994 [15].

The 1990s signified a move from stereotaxic robotic systems to the second-generation surgical robots, i.e., rigid yet dexterous robots for *Minimally Invasive Surgery* (MIS). The ZEUS platform (Computer Motion, Goleta, USA) [16] is the

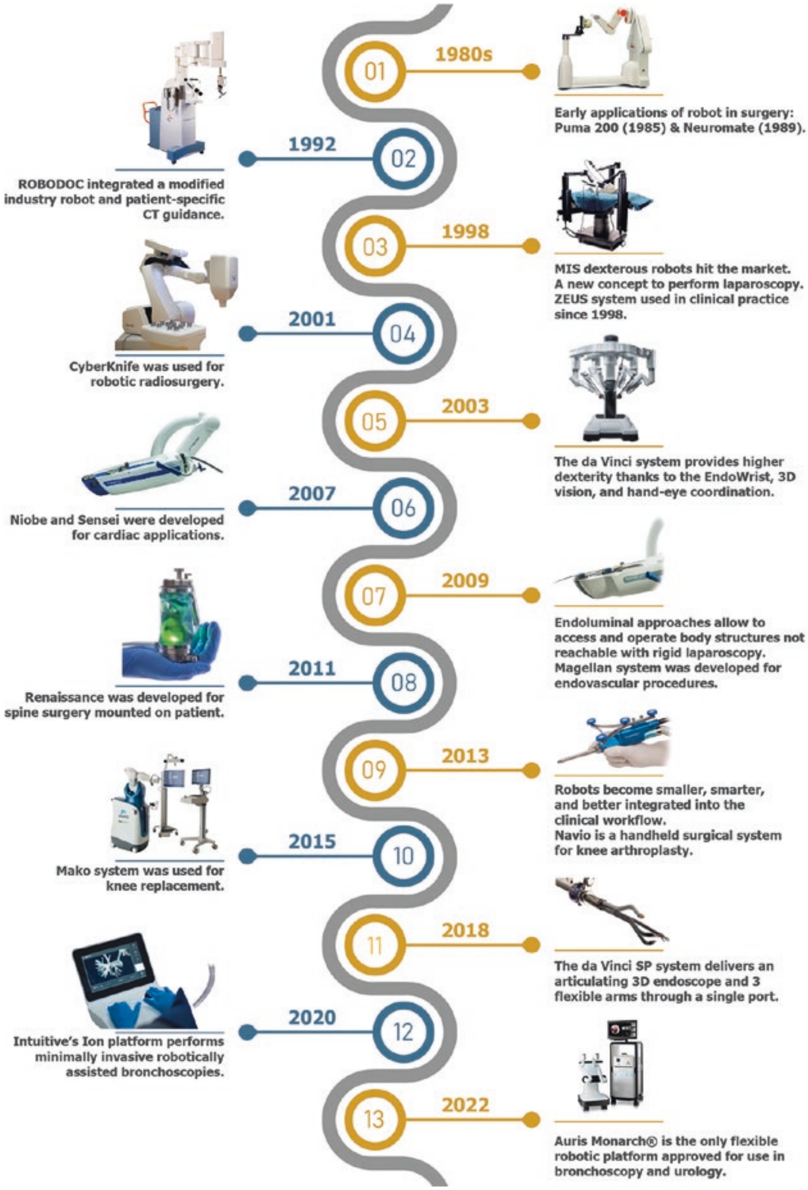

Fig. 1.2 Timeline of surgical robots. Since the first application of a robot in surgery in 1985, a growing number of robotic surgical platforms have been developed and applied to several clinical specializations. From bulky industrial arms adapted to be used in clinical applications—typical of the infancy of robotic surgery—robotic platforms have been bespoke designed to facilitate clinical usability and have become smaller and smarter. This figure reports key milestones in robotics surgery (only commercial platforms) over the last 40 years. Neuromate, Renishaw, © 2023; ROBODOC (CC BY 4.0); ZEUS/AESOP, © Computer Motion; CyberKnife, (CC BY 2.0); da Vinci/da Vinci SP/Ion, Intuitive Surgical Inc., © 2023; Sensei and Niobe (adapted with Springer Nature permission from [13]); Mazor Robotics Renaissance, Mazor Robotics; Navio, Smith & Nephew, © 2023; Mako, Stryker, © 2023; Monarch, Johnson & Johnson MedTech, © 2023

first platform developed for laparoscopy in 1998. It presents several robotic arms that operate inside the patient controlled by the surgeon sitting on a remote console. ZEUS was first applied to cardio-surgery and became famous in 2001 for the trans-oceanic cholecystectomy successfully performed by Marescaux and colleagues [17]. A patient in Strasbourg, France, had her gall bladder removed using ZEUS and was teleoperated by surgeons in New York. The da Vinci system (Intuitive Surgical, Sunnyvale, USA)—now likely the most famous commercial surgical robot worldwide—replaced ZEUS in 2003. The da Vinci systems feature immersive 3D visualization of the surgical scene via a remote console that allows the teleoperation of the laparoscopic instruments. Such configuration allows hand–eye coordination while providing stereo-vision of the surgical field, something not possible in standard laparoscopy. Intuitive Surgical developed many versions of the da Vinci system (e.g., the multi-arm version da Vinci Xi, and the single port version da Vinci SP), which have been used in many clinical applications such as cardiosurgery, colorectal surgery, prostatectomy, and many others [18].

The evolution of surgical robots toward smaller and smarter devices continues in the first decade of this millennium, allowing robots to be used in transluminal or endoluminal procedures. The third generation of surgical robots, i.e., flexible robots for MIS, includes small and steerable devices, such as robotic catheters or snake-like robots, which can access and operate in constrained regions of the human body not previously reachable with rigid laparoscopy. Endovascular procedures can be executed under robotic assistance, using, for example, the two major commercial platforms developed by Hansen Medical (acquired by Auris Health Inc., Redwood City, USA): the Sensei X2 (for *electrophysiological* (EP) procedures) and the Magellan (for endovascular applications) [19, 20]. The i-Snake developed by Yang and his colleagues [21], a snake-like system, allows exploration of a large area of the anatomy through *Natural Orifice Transluminal Endoscopic Surgery* (NOTES) without requiring laparoscopic-style external manipulation, and it has full retroflection capabilities [22].

Concentric tube robots [5] address the limitations of catheter robots by providing higher stiffness while maintaining the required steerability. They are created by a number of pre-curved interconnected elastic tubes that steer when translated and rotated with respect to one another. Since 2005, this technology has become attractive for robot-assisted surgical applications thanks to the pioneering work of Sears & Dupont [23], Webster [24], and Furusho et al. [25], and further evolved to the current stage thanks to technical advances in design [26], control [27], sensing [28], and image guidance [29]. For example, the Monarch platform (Auris Health Inc., Redwood City, USA) integrates robotics and enhanced navigation (3D imaging and sensing) for bronchoscopy applications and received *Food and Drug Administration* (FDA) approval in April 2018. Untethered micro-surgical devices, such as wireless capsules for endoscopy and micro- and nano-robots, are the fourth generation of surgical robots [30]. Endoscopy capsules were introduced in the early 2000s and have evolved thanks to the research of several groups worldwide [31–33], becoming an alternative to traditional endoscopy of the *gastrointestinal* (GI) tract [31–34].