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Medical Robotics: Opportunities in China

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Abstract

Medical robotics is a rapidly advancing discipline that is leading the evolution of robot-assisted surgery, personalized rehabilitation and assistance, and hospital automation. In China, both research and commercial developments in medical robotics have undergone exponential growth in recent years. In this review, we first give an overview of the clinical and social demands that motivate the rapid development in medical robotics. For each subdiscipline (surgery, rehabilitation and personal assistance, and hospital automation), we then summarize the major research projects sponsored by National Key Research and Development Programs. The remaining technical, commercial, and regulatory challenges are highlighted. This review also outlines some of the new opportunities in endoluminal and interventional robotics, micro- and nanorobotics, soft exoskeletons, intelligent human–robot interaction, and telemedicine and telesurgery, which may support the general uptake of robotics in medicine.

1. INTRODUCTION

Medical robots include robots used for surgery, automated diagnosis and treatment, patient care, rehabilitation training, and hospital automation; they are able to assist and/or cooperate with medical staff in different clinical settings and show good adaptability and interactivity (1–4). In recent years, allied technologies in robotics, including AI, microelectronics, soft and smart materials, and microfabrication technologies (5–7), have inspired the development of new generations of medical robots that are agile and intelligent (1, 4). This article categorizes medical robotics, as shown in **Figure 1**, into three groups according to their applications: surgical robots, rehabilitation and assistive robots, and hospital automation robots. For each subgroup, we discuss the associated clinical requirements and unique research and translational challenges.

In the early 1950s, surgical practice began to move from traditional open surgery to minimally invasive surgery, and in the 1980s, industrial robots were first adapted for surgery (8). Since then, robot-assisted surgery has been explored extensively (3, 9), ranging from mechanically grounded platforms (10) to compact, handheld systems (11). With continuing developments in the last three decades, surgical robotics has grown from a niche field of research to an emerging field of innovation with demonstrated advantages in several surgical specialties, particularly orthopedics and urology (3, 10, 12). One of the representative surgical robots is the da Vinci robot developed by Intuitive Surgical (Sunnyvale, California) for laparoscopic surgery (13). Surgical robots are poised to maximize the clinical advantages of minimally invasive surgery (14), enabling precise manipulation of surgical instruments, intuitive hand–eye coordination, and the ability to work beyond human dexterity in a small operation space (12).

Another important area of medical robotics is in rehabilitation and personal assistance. For patients with physical or cognitive impairments, there is a pressing need to either improve the recovery of their physical functions through therapeutic training processes or provide general assistance for their activities of daily living (15). Rehabilitation robotics is the combination of rehabilitation medicine and robotics technology, which can offer robot-assisted therapies or enable automated therapeutic training and recovery (16). Compared with traditional treatment methods, rehabilitation robots can not only ensure the efficiency and consistency of the therapeutic process but also provide objective evaluation of the efficacy of the rehabilitation process (17). Assistive robots, including robots for either functional enhancement [e.g., exoskeletons (18, 19)] or functional compensation [e.g., prostheses (20, 21) and intelligent wheelchairs (22)], are aimed at helping individuals with impaired physical functions to better manage activities of daily living, supporting independence and reducing the demands on nursing and other supportive staff (23, 24).

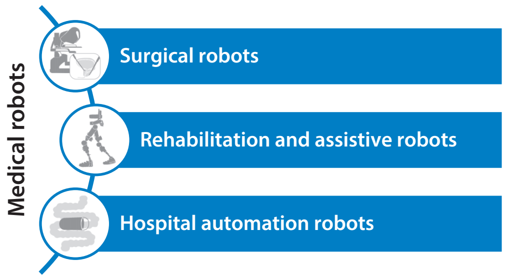

Figure 1

Taxonomy of medical robotics.

The third category of medical robotics is concerned with hospital automation. It includes robots for automated diagnosis and testing, pharmacy work, and hospital logistics as well as those for nursing homes and rehabilitation centers. A service robot can provide ancillary services in hospitals, including medical consultation, hospital logistics, patient transportation, intensive care, and other labor-intensive tasks. Since the beginning of the coronavirus disease 2019 (COVID-19) pandemic, a variety of hospital automation robots have emerged to help protect both hospital staff and patients from potential infection risks, reducing the spread of the coronavirus and performing routine tasks such as surveillance, goods delivery, disinfection, temperature measurement, and nucleic acid testing (25, 26). We also include diagnosis and treatment robots in this category, as they are designed to provide intelligent and accurate diagnosis and treatment through nonsurgical means. These robots, which range from micro- and nanoscales (27) to macroscales, can be applied to various scenarios, including high-throughput testing (28), drug or cell delivery (29), and examination [e.g., capsule endoscopy (30)].

Medical robotics is one of the most advanced fields of robotics, but it is faced with long development cycles, stringent regulatory processes, and high technical barriers. Currently, European and American companies with innovative core technologies are leading the way and have established a dominant market share globally (31). Driven by the huge clinical demand and guided by national policies (e.g., Healthy China 2030), China has invested significantly in medical robotics in recent years, and this field is now becoming one of the most active sectors in the Chinese healthcare market.

2. MOTIVATIONS FOR DEVELOPING MEDICAL ROBOTICS IN CHINA

The development of medical robotics in China faces several challenges in such a large country. In this section, we briefly discuss motivations for developing medical robotics in China, which are driven by social factors, clinical demand, market needs, and investment.

2.1. Social Factors

Many social factors are influencing the evolution of medical robotics in China; three important factors discussed in this review are the country's large and aging population, economic development, and limited medical resources.

2.1.1. Large and aging population. China is the most populous country in the world, with more than 1.41 billion people, according to the Seventh National Population Census released in 2021 (32). The population is also rapidly aging: There are 264.02 million people over age 60 and 190.64 million over age 65, accounting for 18.70% and 13.50% of the entire population (32). As a result, there will inevitably be major demand for chronic disease management, particularly for age-related diseases such as neurodegenerative diseases (33), bringing both challenges and opportunities for robotics.

2.1.2. Economic development. In recent decades, China's economy has grown quickly through continuing efforts in industrial transformation and upgrades. In 2019, China's gross domestic product (GDP) was close to $14.3 trillion, with a growth rate of 6.1% and an increase of $1.3 trillion compared with the previous year. China's GDP ranks second in the world and accounts for one-sixth of the world's GDP (34). With rapid economic development, the disposable income and general consumption capacity of Chinese residents continue to grow. In 2019, per capita disposable income reached $4,434, with 8.9% year-on-year growth (5.8% after deducting price factors)

(34). As a direct result, the demand for high-quality medical treatment is on the rise, not only for critical care but also for quality of life after treatment.

2.1.3. Limited medical resources. Despite the rapid economic growth, high-quality medical resources in China are limited. A 2016 study revealed that China ranks 48th in the world in the Healthcare Access and Quality index, with an average score of 78 (35). This index is correlated with the number of physicians, nurses, and hospital beds per 1,000 people in the population. For medical resources, China has only 2.77 licensed doctors and 3.18 registered nurses per 1,000 people, well below the numbers in the developed countries. For high-quality medical resources, according to a report released by National Health Commission in 2020 (36), there are only approximately 2,749 AAA (the highest standard) and 9,687 AA hospitals in China, which are struggling to meet the medical care needs of such a large population. There is also a major regional disparity in terms of medical resource allocation in China (37), and this gap is significant between urban and rural areas. For instance, the scores on the Healthcare Access and Quality index vary from 91.5 in Beijing to less than 50 in some rural areas (35). Medical robotics can potentially help to ensure a consistent standard of healthcare while reducing the uneven distribution of medical resources and the workload of medical staff.

2.2. Clinical Demand

Due to changes in lifestyle and dietary habits, the incidence and mortality rates of diseases exhibit changing characteristics in China (38). As revealed by the Global Burden of Disease Study 2017 (39), high intake of sodium is the leading dietary risk in China; other risks include low intake of whole-grain foods, smoking, and low activity, as well as the increased pace and pressure of working life. China now has the highest age-standardized rate of death from diet-related cardiovascular disease [299 deaths (range of 275–3,240) per 100,000 people] and the highest rates of diet-related cancer deaths and disability-adjusted life years [42 deaths (range of 34–49) and 889 disability-adjusted life years (range of 744–1,036) per 100,000 people].

As reported in a recent study (40), stroke, ischemic heart disease, lung cancer, chronic obstructive pulmonary disease, liver cancer, road traffic, stomach cancer, Alzheimer's disease, neonatal disease, and hypertensive heart disease have become the top 10 causes of death in China (see **Figure 2**). It should be pointed out that, compared with other countries, China also has exceptionally high incidence and mortality rates of stroke, chronic obstructive pulmonary disease, and lung, liver, stomach, and esophageal cancers.

2.2.1. Cardiovascular and cerebrovascular diseases. As predicted by the *Report on Cardiovascular Health and Diseases in China 2019* (41), there are approximately 330 million people suffering from cardiovascular and cerebrovascular disease in China (see **Figure 3**). As a result,

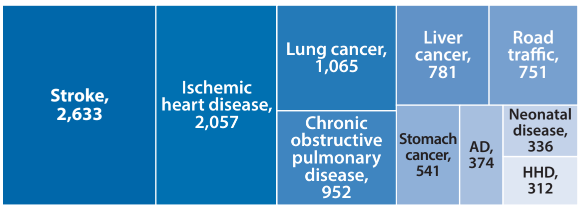

Figure 2

Top 10 causes of death in China. Each number indicates years of life lost per 100,000 people. Abbreviations: AD, Alzheimer's disease; HHD, hypertensive heart disease.

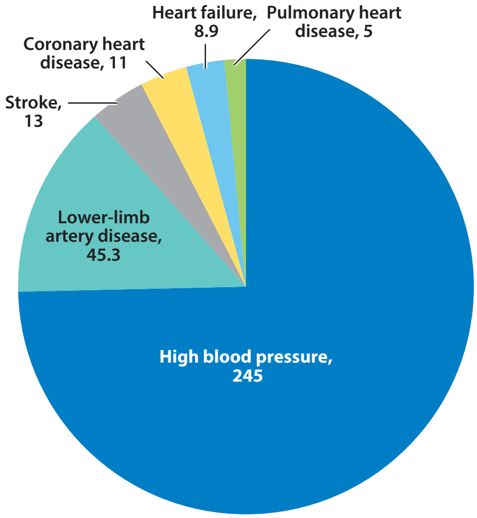

Figure 3

Number of people (millions) suffering from cardiovascular and cerebrovascular disease in China.

cardiovascular and cerebrovascular diseases, such as stroke, ischemic heart disease, and hypertensive heart disease, have been the major causes of death in China, accounting for 45.91% of all deaths in rural areas and 43.56% in urban areas. Early screening is essential to establishing risk factors for cardiovascular and cerebrovascular diseases and to detecting the pathological changes of these diseases at an early stage, enabling the adoption of scientific prevention and treatment measures. Cardiovascular and cerebrovascular diseases can now be treated with minimally invasive vascular intervention methods, which can reduce access trauma and improve patient prognosis. However, the existing approaches have certain limitations (e.g., limited control over surgical instruments and high skill requirements for surgeons to operate), which opens new opportunities for robot-assisted interventions.

China has the highest risk of stroke in the world (39.3% for the entire population) and the highest risk in males (41.1%) (42). In addition to stroke-related fatalities, surviving patients have major degradations of their musculoskeletal and/or neurological systems, which directly affects their physical motion and cognition. Hence, it is of great importance to provide long-term rehabilitation training for patients after a stroke. As illustrated by Wu et al. (43), only 30–60% of stroke patients are able to receive rehabilitation therapy in a hospital after an initial neurology or neurosurgery treatment. Most of these people have access only to isolated physical therapy for motor function, with fewer than 10% of patients able to receive physiotherapy, occupational therapy, speech–language therapy, or psychotherapy.

2.2.2. Cancer.

Sadly, China has the largest number of new cases and deaths from cancer in the world. As released in the Global Cancer Observatory (**https://gco.iarc.fr**) by the World Health Organization's International Agency for Research on Cancer, there were an estimated 19.29 million new cases and 9.96 million deaths worldwide in 2020, of which 4.57 million new cases (23.7%) and 3 million deaths (30.1%) occurred in China.

As shown in **Figure 4*a***, because of risk factors due to environmental, dietary, and lifestyle changes (38, 39), the incidence rates of some cancers in China are significantly higher than the world average; new cases in China account for 53.64%, 45.30%, and 43.89% of new cases of

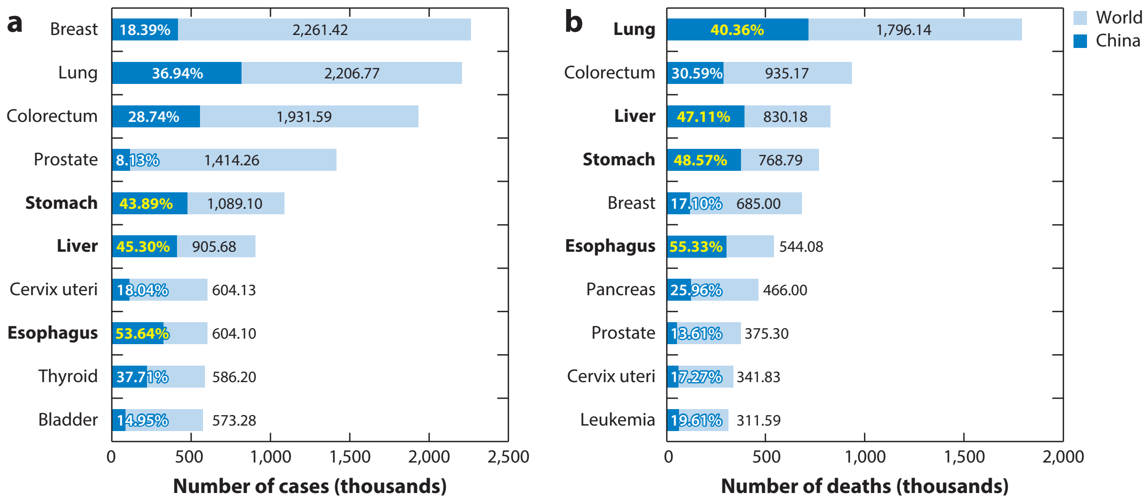

Figure 4

Estimated number of (*a*) new cases of the top 10 cancers and (*b*) deaths from the top 10 cancers worldwide and in China in 2020. The percentages indicate the proportions of cases and deaths in China relative to the rest of the world; boldface yellow percentages highlight exceptional proportions that exceed 40%.

esophageal, liver, and stomach cancer worldwide, respectively. These high-incidence cancers also lead to a large number of deaths in China, accounting for more than 40% of deaths worldwide (see **Figure 4*b***). Due to smoking and air pollution, lung cancer has the highest incidence and death rates of all cancers in China. The high incidence and mortality rates of cancers have driven the country's innovation in medical robots related to early diagnosis and surgical treatment.

2.3. Market and Investment

As a cutting-edge technology for clinical use, the development of medical robotics is heavily reliant on the market size and the amount of investment.

2.3.1. Global and Chinese market. In recent years, the global market for medical robotics has been growing rapidly, and the total size is expected to reach $20.7 billion in 2021, with a 15% average annual growth rate. The market is distributed mainly in North America, Europe, and the Asia-Pacific region, which are also active in the global economy. **Figure 5*a*** shows the market sizes in the world and in China. It can be seen that the Chinese market size is only approximately 5% of the global market size. However, the growth rate of the Chinese market is high (approximately 30% per year). The estimated market size in China will exceed $1 billion in 2021, and there is still huge potential for growth.

2.3.2. Investment in medical robotics. Due to the huge demand in China, rehabilitation and assistive robots account for the highest proportion of domestic medical robot enterprises, at 47% (**Figure 5*b***). Recently, investment has poured into surgical and hospital automation robots, achieving integrated development across all areas of medical robotics. The largest amount of investment, approximately 1 billion RMB, was given to Chinese unicorn companies in 2017 (44). Due to the recent COVID-19 pandemic, the need for intelligent hospital service robots exploded in 2020 for tasks such as disinfection, delivery, and nucleic acid testing. Such robots can effectively reduce the infection risk for frontline medical staff (25, 26).

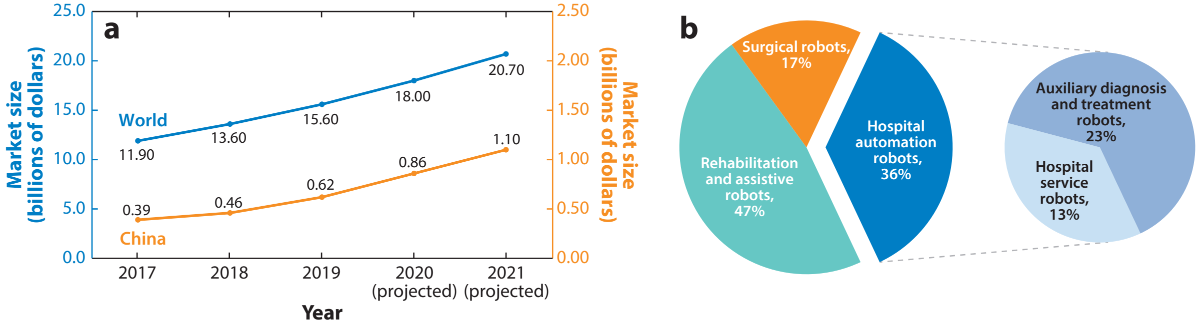

Figure 5

(*a*) Market sizes of medical robotics in the world and in China from 2017 to 2021. (*b*) Market distribution of different medical robots in China in 2019. Data are from Reference 44.

3. CURRENT RESEARCH IN MEDICAL ROBOTICS IN CHINA

China has stepped up research efforts on medical robotics in the past two decades. As shown in **Figure 6**, there has been rapid growth in the number of research papers with at least one Chinese author published in the combined fields of biomedical engineering and robotics (the same search criterion reported in Reference 45 through 2019). The first peak occurred in 2008, after the first da Vinci robot was deployed in China; the second appeared in 2017 and reached a similar number as the United States. This may have been because the various National Key Research and Development (R&D) Programs were established to give strong support to the development of medical robotics, and some domestic medical robots gained approval from the Chinese Food and Drug Administration (CFDA, before September 2018) or National Medical Products Administration (NMPA, after September 2018).

3.1. National Policy and Guidance

In recent years, the Chinese government has introduced a series of medium- and long-term plans for science and technology development, reforming the national health system, and carrying out

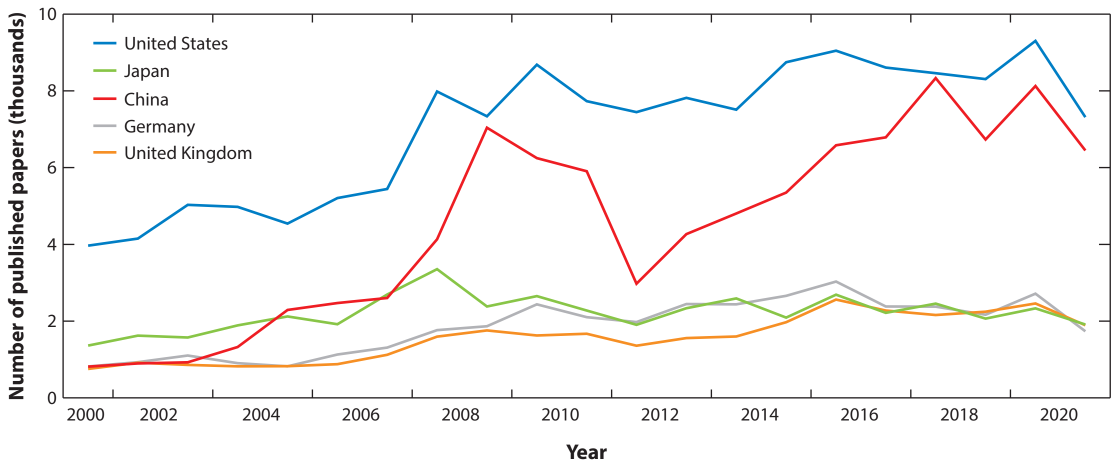

Figure 6

Number of papers published by authors from different countries in the field of biomedical engineering and robotics between 2000 and 2020.

industrial upgrade strategies, among which the development of high-end medical equipment (e.g., medical robotics) is an area of focus.

In terms of overall planning, the Healthy China 2030 plan, announced in 2016, emphasized that innovation and informatization are critical factors for public health and that using medical robots could address the major gap between the supply of and demand for medical resources. The State Council has proposed developing medical robots and accelerating the digitization of intelligent medical devices in a document titled "Guiding Opinions of the General Office of the State Council on Promoting the Healthy Development of the Pharmaceutical Industry." In March 2017, the State Council additionally highlighted the development of surgical robots and intelligent systems for realizing human–machine cooperative intelligent diagnosis and treatment in another document, titled "Development Plan for a New Generation of Artificial Intelligence." In its future manufacturing strategy, it emphasized the development of medical robots in the field of biomedicine and high-performance medical devices, which it listed as one of 10 significant fields.

In terms of research, the Ministry of Science and Technology established a series of National Key R&D Programs to support medical robotics development. These programs covered the research topics of surgical robots, rehabilitation and assistive robots, and hospital automation robots, focusing on fundamental theories, key technologies, core components, prototype systems, and application demonstrations. Through the close cooperation of industry, universities, and research institutes, many critical issues have been addressed, and some of these projects have completed clinical translation.

In terms of industrialization, in March 2016, the Ministry of Industry and Information Technology, the National Development and Reform Commission, and the Ministry of Finance jointly issued a document titled "13th Five-Year Plan for Robot Industry Development (2016–2020)," aiming to make breakthroughs and reach a similar level as foreign counterparts in the core components of robots (e.g., precision reducers, servomotors, drivers, and controllers). The development of high-end medical robots will benefit from innovation in upstream core components, promoting the clinical translation and industrialization of domestic medical robots.

3.2. National Key Research and Development Programs on Medical Robotics

In the past few decades, a significant number of projects related to medical robotics have been sponsored by the National Natural Science Foundation of China, the Ministry of Science and Technology, and other funding bodies. Specifically, the National Key R&D Programs sponsored by the Ministry of Science and Technology have been the main impetus for recent medical robotics development in China. The three main efforts are the Intelligent Robotics (launched in 2017), Technology Response to Active Health and Aging (also launched in 2017), and Digital Diagnosis and Treatment Equipment (launched in 2018) programs, which cover either fundamental research or system designs for different types of medical robotics. (Note that other National Key R&D Programs have also involved research on medical robots but may not be covered in this review.) **Figure 7*a*** shows the number of medical robotics projects approved from 2017 to 2020. Owing to the strong support of the National Key R&D Programs, there has been great progress in medical robotics as well as robot-related technologies in China.

3.2.1. Intelligent Robotics program.

The Intelligent Robotics program aims to make breakthroughs in the fields of mechanisms, materials, sensing, control, and bionics; robot learning and cognition; human–robot interaction and collaboration integration; and other major frontier technologies. It also supports research working on the development of upstream core components of robots, high-precision sensors, embedded software, the safety and reliability of robotic systems, and other key issues, thus enhancing the competitiveness of domestic robots in the world market.

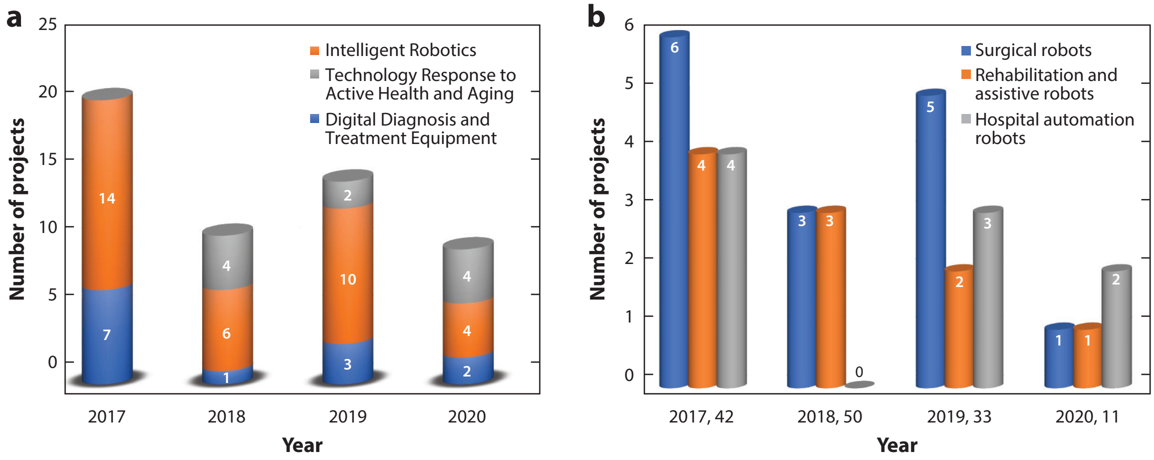

Figure 7

(*a*) Number of projects on medical robotics supported by three National Key Research and Development Programs (Intelligent Robotics, Technology Response to Active Health and Aging, and Digital Diagnosis and Treatment Equipment) from 2017 to 2020. (*b*) Projects related to surgical robots, rehabilitation and assistive robots, and hospital automation robots sponsored by the Intelligent Robotics program in each of these years, where the number given after each year indicates the total number of projects sponsored by the program in that year.

Of the 136 projects approved from 2017 to 2020, 34 (25%) were related to medical robotics, which emphasizes the significance of medical robotics in the national strategy. **Figure 7*b*** shows the number of sponsored projects on surgical, rehabilitation and assistive, and hospital automation robots as well as the total number of projects in each year.

3.2.2. Technology Response to Active Health and Aging program. In response to the Healthy China 2030 strategy, the Technology Response to Active Health and Aging program focuses on active health, particularly health imbalance identification, health risk assessment, and health self-management. The main objective is to make breakthroughs in the areas of quantitative health status analysis, health data fusion analysis, personalized health guidance, and health support for the elderly, with the ultimate goal of developing key technologies (e.g., rehabilitation and assistive robotics) for achieving active health and providing intelligent assistance for the aging population.

3.2.3. Digital Diagnosis and Treatment Equipment program. The Digital Diagnosis and Treatment Equipment program focuses on developing integrated systems with independent core components and technologies for early and accurate diagnosis and minimally invasive and precise treatment of major illnesses. It also aims to promote the improvement of testing standards, the creation of standards, the evaluation of demonstration applications, and the acceleration of innovation and industrial supply chains for intelligent medical devices.

3.3. Current Medical Robotics in China

In this section, we discuss the historical development and recent progress of surgical, rehabilitation and assistive, and hospital automation robots in China.

3.3.1. Surgical robotics. Compared with Europe and America, the development of surgical robotics in China started late, but it is now at a stage of rapid progress. In May 1997, the Navy

Table 1 Projects related to surgical robotics supported by National Key Research and Development Programs from 2017 to 2020

Program	Year	Project topic	Category
Intelligent Robotics	2017	Retinal surgery robot (48, 49)	Other
		Minimally invasive oral and maxillofacial surgery robot (50, 51)	Orthopedics
		Knee replacement surgery robot (52)	Orthopedics
		Real-time navigation and puncture robot (53)	Other
		Telesurgery robot for bone trauma (54, 55)	Orthopedics
		Minimally invasive vascular interventional surgery robot (56)	Interventional
	2018	Surgical robot for accurate reduction of lower limb fracture (57)	Orthopedics
		Spinal laminectomy surgery robot (58)	Orthopedics
		Surgical robot for narrow cavity of human body (59, 60)	Transluminal
	2019	Surgical robot for diagnosis and treatment in digestive tract (61, 62)	Transluminal
		Femtosecond laser minimally invasive surgical robot (63)	Transluminal
		Multi-instrument delivery of vascular interventional surgery robot (64)	Interventional
		Cochlear implant robot (65)	Other
		Human–machine cooperative craniotomy robot (66)	Orthopedics
	2020	Surgical robot for closed reduction of complex fractures (67)	Orthopedics
Digital Diagnosis and Treatment Equipment	2017	Multiport laparoscopic surgical robot[a] (68–71)	Laparoscopic
		Orthopedic surgical robot[a] (72, 73)	Orthopedics
		Single-port laparoscopic surgical robot[a] (74, 75)	Laparoscopic
	2019	Development of core components of surgical robot system (76, 77)	Other
		Minimally invasive surgical robot for head and neck region (78)	Orthopedics

[a]Parallel projects were also supported for specific research topics.

General Hospital and the Robotics Institute of Beihang University jointly developed the first medical robot and used it in stereotactic radiotherapy (46, 47), which was one of the earliest clinical applications in China. An orthopedic robot system called GD-A (Tinavi Medical Technologies Company) was approved by the CFDA in February 2010, becoming the first surgical robot with a registered license in China. In 2013, a National High-Tech R&D Program on minimally invasive abdominal surgical robots jointly developed by several leading universities and hospitals was completed, which marks the progress of minimally invasive surgical robots in China. Recently, an increasing number of projects related to surgical robotics have been supported by National Key R&D Programs (**Table 1**), which has promoted the development of advanced and specialized surgical robots. We categorize these projects into four groups based on their applications: orthopedic surgical robots, laparoscopic surgical robots, transluminal endoscopic and interventional robots, and other surgical robots.

3.3.1.1. Orthopedic surgical robots. Orthopedic robots are important auxiliary surgical tools that are suitable for various orthopedic surgeries (e.g., trauma, skull, and spine and joint surgeries) and can assist doctors in preoperative planning and intraoperative guidance. Robot-assisted orthopedic surgery has the advantages of precise positioning, short operation time, low radiation exposure for surgeons, and fast patient recovery. As can be seen in **Table 1**, the development of surgical robots on minimally invasive oral and maxillofacial surgery (50, 51), knee replacement (52), craniotomy (66), spinal laminectomy (58), and reduction of fractures (57, 67) was strongly supported. In addition, a robotic system for telesurgery was explored for bone trauma treatment (54, 55). It is noteworthy that parallel projects on orthopedic surgical robots were supported by the Digital Diagnosis and Treatment Equipment program in 2017 (72, 73).

3.3.1.2. Laparoscopic surgical robots. Compared with patients who undergo conventional open surgery, patients who undergo robot-assisted laparoscopic surgery can have less trauma and post-operative pain, shorter hospital stays, and faster recovery. Current laparoscopic surgical robots are complex systems, typically composed of three parts: a surgeon console, robot arms, and an imaging system. To help domestic robots achieve a similar level as the da Vinci robot, research on multiport and single-port laparoscopic surgical robotics was supported by the Digital Diagnosis and Treatment Equipment program. A domestic multiport laparoscopic robot system was then jointly developed by Tianjin University, Central South University, and WeGo Robotics Company (68, 69), and a single-port laparoscopic robot system was developed by Shanghai Jiao Tong University (74, 75).

3.3.1.3. Transluminal endoscopic and interventional robots. Endoscopic robots can use a compliant approach to accurately reach a lesion through a natural orifice such as the nose, mouth, or rectum (79). At the same time, they can deploy an electric hook, knife, forceps, and other tools to carry out minimally invasive operations. Compared with laparoscopic surgical robots, they can reduce the damage to healthy tissue and avoid scars on the skin. Most cardiovascular and cerebrovascular diseases can be treated by endovascular intervention, which can effectively reduce trauma and improve patient prognosis. Hence, the development of transluminal endoscopic and interventional robots has attracted much attention in China. The Intelligent Robotics program supported research on a minimally invasive vascular interventional surgical robot (56) and its core technology for multi-instrument delivery (64) in 2017 and 2019, respectively. The sponsored transluminal endoscopic robots were designed to perform simultaneous diagnosis and treatment in various narrow orifices of the human body (59–63).

3.3.1.4. Other surgical robots. Other projects have been supported for the development of robotic systems related to retinal surgery (48, 49), cochlear implants (65), and real-time punctures (53). In addition, separately from programs that supported research on the design and application of surgical robots, the Digital Diagnosis and Treatment Equipment program was established in 2019 to focus on the core components of surgical robots (76, 77).

3.3.2. Rehabilitation and assistive robotics. With an aging population and the rapid increase in disabilities caused by various diseases (e.g., stroke, spinal cord injury, and brain injury), the demand for rehabilitation and assistive equipment is growing substantially. Rehabilitation robots aim to help people complete desired body movements, carry out the functions of walking, and perform rehabilitation training and treatment. In the current market of medical robots, rehabilitation and assistive robots make up the largest proportion of the three categories. **Table 2** summarizes the projects related to rehabilitation and assistive robots sponsored by recent National Key R&D Programs. It is noteworthy that the Technology Response to Active Health and Aging program has focused mainly on robotic systems for rehabilitation and personal assistance.

3.3.2.1. Exoskeletons. Because of the aging population, there is major demand for lightweight, wearable rehabilitation equipment, and exoskeleton robots have therefore become popular all over the world. The most famous of these robots include those made by Ekso Bionics, ReWalk Robotics, Cyberdyne, Hocoma, and Rex Bionics, among others. In China, a lower-limb exoskeleton developed by Beijing Ai-Robotics Technology Company was the first to be approved by the CFDA. In addition, the Intelligent Robotics and Technology Response to Active Health and Aging programs funded several projects to address the key technical challenges of power-assisted exoskeletons (82–85) and orthoses (99) designed to assist people with impaired physical functions.

Table 2 Projects related to rehabilitation and assistive robotics supported by National Key Research and Development Programs from 2017 to 2020

Program	Year	Project topic	Category
Intelligent Robotics	2017	Human-machine interaction and mechatronics integration (80, 81)	HMI
		Power-assisted exoskeleton (82, 83)	Exoskeleton
		Walking robot for paraplegic patients (84, 85)	Exoskeleton
		Rehabilitation robot for stroke patients (86, 87)	Rehabilitation
	2018	Assistive robot for semidisabled elderly (88, 89)	Assistive
		Bidirectional neural pathways for an intelligent upper-limb prosthesis (90, 91)	Prosthesis
		Intelligent powered lower-limb prosthesis (92, 93)	Prosthesis
	2019	Rehabilitation robot for balance disorders (94)	Rehabilitation
		Rehabilitation robot for patients with spinal cord injuries (95, 96)	Rehabilitation
	2020	Invasive brain–computer interface (97)	HMI
Technology Response to Active Health and Aging	2018	Intelligent prosthetic knee joint (98)	Prosthesis
		Intelligent orthosis (99)	Exoskeleton
		Virtual reality for rehabilitation training (100)	Rehabilitation
		Rehabilitation training system for cognitive impairment (101, 102)	Rehabilitation
	2019	Rehabilitation training system for limb motor impairment[a] (103, 104)	Rehabilitation
	2020	Intelligent multimodal mobile robot[a] (105, 106)	Assistive
		Intelligent and dexterous upper-limb prosthesis[a] (107, 108)	Prosthesis

Abbreviation: HMI, human–machine interface.
[a]Parallel projects were also supported for specific research topics.

3.3.2.2. Prostheses and human–machine interfaces. Prostheses can help amputees and paralyzed patients to complete activities of daily living. In recent years, research efforts have been made to develop upper-limb prostheses (90, 91, 107, 108), lower-limb prostheses (92, 93), and prosthetic knee joints (98). Compared with passive prostheses, the motor control of active prostheses typically incorporates a bidirectional human–machine interface (109), where the prostheses can detect users' motion intention and conduct the desired movements, and the sensory information perceived by the prostheses is transferred to users as feedback. Research on bidirectional neural pathways (90, 91), human–machine interaction (80, 81), and human–machine interfaces (97) has been supported. In practice, various sensing modalities, including muscle activities and brain signals, can be used to form the interfaces. Fundamental problems of human–machine interfaces have also been widely explored and supported by the Coexistence–Cooperative–Cognitive Robots (Tri-Co Robots) project sponsored by the National Natural Science Foundation of China.

3.3.2.3. Rehabilitation training robots. Rehabilitation training aims to use multidisciplinary treatments to improve the movement capability of patients with degradation in their neurological and/or musculoskeletal systems. Various rehabilitation training robots have been developed in the past few decades, which can be categorized into end-effector-based systems and exoskeleton-based systems (110). As a huge number of people have suffered strokes and spinal cord injuries, recent National Key R&D Programs have widely supported the development of rehabilitation training robots for these patients (86, 87, 94, 99, 103, 104). Recently, advanced virtual-reality and augmented-reality technologies have been incorporated into rehabilitation training robots to enhance the engagement of users and guide them to be trained in a controlled environment (111); for example, the Technology Response to Active Health and Aging program has sponsored research on effective virtual-reality-based rehabilitation robots (100). In addition to training for people with physical impairments, there is a need for rehabilitation training robots that can help patients with

Table 3 Projects related to hospital automation robotics supported by National Key Research and Development Programs from 2017 to 2020

Program	Year	Project topic	Category
Intelligent Robotics	2017	Intelligent nursing robot (112, 113)	Service
		Urethral interventional D&T robot (114, 115)	D&T
		D&T robot for skull base and face punctures (116)	D&T
		Robot for use in nursing homes (117)	Service
	2019	Micro- or nanorobot for targeted drug delivery (118, 119)	D&T
		Minimally invasive brachytherapy robot (120, 121)	D&T
		Intelligent diagnosis robot for colonoscopy (122, 123)	D&T
	2020	Bronchial interventional robot for diagnosis of pulmonary micronodules (124, 125)	D&T
		Biohybrid robot based on living cell (126, 127)	D&T
Digital Diagnosis and Treatment Equipment	2020	Surgical planning and real-time navigation (128, 129)	D&T
		Augmented-reality-based minimally invasive precision D&T in orthopedics (130, 131)	
	2018	Implants and interventional therapy (132, 133)	D&T
	2020	Intelligent robot for inspection rounds and critical care[a]	Service

Abbreviation: D&T, diagnosis and treatment.

[a]Includes two emergency projects on hospital service robots that were issued to combat the COVID-19 pandemic.

cognitive impairments (101, 102), as the number of patients suffering from Alzheimer's disease, Parkinson's disease, or dementia has significantly increased in China.

3.3.2.4. Mobile assistive robots. Assistive robots incorporated with mobile platforms enable users to achieve free movement in various environments. The critical technologies related to mobile assistive robots are typically related to perceiving the environment and the robot's own status based on information collected from different sensors (22). The development of these robots has been widely supported in recent years, with the goal of assisting the disabled population in rehabilitation centers and home-based environments (88, 89, 105, 106).

3.3.3. Hospital automation robotics. Various types of hospital automation robots have emerged for providing medical services, healthcare services, diagnosis and treatment, nursing and inspection rounds, and logistics in hospitals and rehabilitation centers. As listed in **Table 3**, we group the projects related to hospital automation robots sponsored by Nation Key R&D Programs into two categories: diagnosis and treatment robots and hospital service robots.

3.3.3.1. Diagnosis and treatment robots. Most diagnosis and treatment robotic systems can be directly integrated with surgical robots, providing either accurate diagnosis or target therapy based on preoperative and intraoperative information. Due to the high dietary risk in the Chinese population, there is great demand for digestive tract endoscopy. Hence, capsule endoscopic robots have attracted extensive attention because they can easily enable comfortable examinations (122, 123). In 2016, NaviCam, a magnetically driven capsule endoscopic robot, was developed by ANKON Technology Company and approved by the CFDA. With the recent advancements in relevant technologies, there has been increasing interest in interventional diagnosis and therapy through natural orifices of the human body [such as the urethra (114, 115), bronchial tube (124, 125), or digestive tract (128, 129, 132, 133)] as well as minimally invasive punctures (116) and brachytherapy (120, 121). Beyond conventional robotic systems, recent attention has also been given to micro- and nanorobotics for cell-level inspection (126, 127) and targeted drug delivery (118, 119).

3.3.3.2. Hospital service robots.

Hospital service robots are typically a combination of mobile robotics augmented with machine vision and AI technologies, which are capable of providing automated service in an indoor environment. One fundamental challenge is the localization and mapping of the robot's surroundings (134), enabling automated navigation within the hospital. As can be seen from **Table 3**, recent research efforts have increasingly focused on developing robots for intelligent nursing (112, 113, 117). In response to the COVID-19 pandemic, two emergency projects in 2020 focused on intelligent robots for inspection rounds and critical care (bottom row of **Table 3**). In addition to research projects supported by various funding bodies, numerous hospital service robots have been extensively studied or have emerged during the pandemic, playing significant roles in logistics, disinfection, sampling, dispensing, and so on. These robots can help to improve treatment efficiency, reduce the risk of infection, and promote scientific and intelligent prevention and control.

4. EMERGING CHALLENGES IN CHINA

As an emerging field, R&D for medical robotics in China is progressively moving toward industrialization but also faces many practical challenges, including upstream supply chains and downstream markets. This section addresses common challenges of medical robotics, including medical data protection, standardization, and regulation.

4.1. Upstream Industry

The current insufficiency of upstream industries in China may create a bottleneck in the future development of medical robotics. Upstream industries typically provide the fundamental hardware components for robots, such as precision servomotors, reducers, controllers, sensors, and chips.

Rotate vector (RV) reducers, which have the advantages of small volume, strong impact resistance, large torque, high positioning accuracy, low vibration, and a large deceleration ratio, have been extensively incorporated in medical robots. Given the limited development of domestic RV reducers, China has started to boost R&D for these components in the past few decades. Although domestic reducers have made remarkable advances with this strong support, their performance (e.g., their accuracy, stability, and consistency) remains inferior to the performance of their foreign counterparts.

Servomotors, which serve as execution units, are one of the core components of medical robots. As with RV reducers, there has been a large gap in quality between domestic and foreign servomotors, and a recent innovative manufacturing plan established a long-term goal to make advances in these components. Domestic servomotor products can now achieve comparable performance to foreign products but only at larger sizes, which impedes their application in some high-end medical robots.

Control systems are responsible for controlling robots based on prescribed programs. At present, both popular controllers and embedded operating systems are dominated by foreign companies; hence, to advance Chinese medical robotics, there is an urgent need for China to develop its own controllers and operating systems.

Sensors give robots the ability to perceive both themselves and the surrounding environment. Currently, high-precision sensors and the chips for domestic sensors are mostly dependent on imports, and domestic sensors account for only 30% of China's sensor market. However, driven by the current policies and market, China has gradually expanded its sensor industry.

4.2. Downstream Market

Downstream of medical robotics is the smart medical market, including hospitals, rehabilitation centers, nursing institutions, and even home-based environments. With China's aging society, the demand for medical robots will inevitably increase. It should be pointed out that there is a huge gap between the number of medical personnel per 100,000 people in China and the number in developed countries (35), and the distribution of medical resources is uneven both between urban and rural areas and among different regions in China (37). Compared with the increasing clinical demand, the growth rate of medical personnel is obviously too slow, and the difference between supply and demand is too large. Hence, medical robots can greatly improve the efficiency and quality of medical services and alleviate the discrepancy between domestic medical supply and demand. It is worth pointing out that the product permeability of medical robots in the downstream market remains low, mainly because of the high cost of medical robots and undeveloped charging and reimbursement policies, resulting in a lack of purchase motivation for downstream medical institutions.

4.3. Medical Data Protection

In the process of implementing precise and personalized medical services, medical robots can generate a large amount of data, including patient personal information, clinical information, medical records, and information collected by various sensors. Without appropriate storage and management, such data may introduce extremely high security risks. For instance, nursing robots participating in the private lives of patients will collect and analyze patients' physiological conditions, eating habits, and daily activities through wearable sensors or even video monitoring, which creates a risk of private data leakage. Network attacks on hospitals and medical robots also dramatically increase the risk of medical data leakage. Hence, it is of paramount importance to set up high security standards and regulations for medical data protection, not only in China but also all over the world, covering areas ranging from data access to data encryption and protection to data sharing.

4.4. Standardization and Regulation

As medical robotics is an emerging industry, standardization has become one of the key issues in its development. Most of the currently available domestic medical robots involve different kinds of open source technologies, leading to inconsistency across hardware and software interfaces, and it is therefore desirable to create a series of standards for safety, testing, interfaces, and even core components, facilitating the adaptation of the research to the relevant industries. To this end, the State Council put forward a document titled "Development Plan of National Standardization System Construction (2016–2020)" to improve standardization in diagnosis and treatment equipment, such as medical robots and household medical devices for healthcare. Medical robots with levels of automation should meet strict requirements. Compared with European and American countries, China is more strict in its clinical trials of medical robots and has more stringent requirements for medical certification. For instance, even when a surgical robot has been approved by the US Food and Drug Administration and has received the European Union's CE mark, it takes approximately two years to apply for NMPA certification when entering the Chinese market. This requirement may slow down the application of medical robots and raise the threshold for domestic medical robot industrialization.

5. FUTURE TRENDS IN MEDICAL ROBOTICS

In the last 30 years, medical robotics has established its role in routine clinical practice, and the pace of its development is expected to accelerate rapidly in the next decade. Key features of future medical robots will be intelligence, miniaturization, light weight, and wearability, enabling minimally invasive, precise, agile, cost-effective, and universal diagnosis and treatment. This section summarizes some exemplar topics of future trends.

5.1. Endoluminal and Interventional Robotics

Laparoscopic surgical robots are currently dominated by the da Vinci robot, and it is time for China to forge international collaborations to develop the next generation of surgical robots, such as endoluminal and interventional robots. In view of their complex operating environments (e.g., the narrow and curved natural orifices of the human body), bioinspired mechanical structures could facilitate the design of microrobots and variable-stiffness continuum robots. Moreover, to achieve early, accurate, and intracavitary interventional diagnosis and treatment, a unified approach for endoluminal intervention with micro- and nanorobotics can be explored, which may potentially leverage the latest breakthroughs in micro- and nanofabrication, smart materials, mechatronics, bioinspired design, biophotonics and imaging, and target therapy for managing early malignancies. We believe that such a robot is capable of reshaping the future of precision surgery.

5.2. Medical Micro- and Nanorobotics

Micro- and nanorobotics are defined by the physical size of the robot, manipulation of micro- or nanoscale objects, or fabrication with micro- or nanoscale accuracy. In the medical field, micro- and nanorobots can be applied in the frontier areas of targeted drug delivery and release, minimally invasive diagnosis and treatment, microscopic detection and sensing, and so on. The development of micro- and nanorobots is in its initial stages all over the world, where the essential problems are manipulation and fabrication. Micro- and nanorobotic manipulation is the method of using robotics-based actuation and sensing to manipulate items on a microscopic level. This focus area involves the development of precision micromanipulators, such as holding pipettes, injectors, electromagnetic actuators, and optical tweezers. Micro- and nanofabrication aims to utilize automated robotics technology to enhance the fabrication of miniaturized structures with high precision. It involves various techniques for adding and removing different materials to and from the products.

5.3. Soft Exoskeletons

Conventional rehabilitation and assistive robots typically consist of rigid structures, which have a large volume and weight, are uncomfortable to wear, and provide inadequate autonomy and interaction. To help overcome these issues, exoskeletons consisting of soft materials or soft structures can provide greater comfort than rigid ones and can help patients avoid secondary injuries. The inherent challenges of applying soft exoskeletons in the future are developing new variable-stiffness materials, accurately modeling the kinematics and dynamics of soft robots, designing dexterous bionic structures, and developing advanced control algorithms. While overcoming the problems of limited driving force and response speed, soft exoskeletons can not only help patients to complete rehabilitation training but also assist in daily activities in a more natural and comfortable way.

5.4. Intelligent Human–Robot Interaction

Human–robot interaction aims to simultaneously understand the capabilities and states of both a human and a robot, constructing an effective bidirectional interaction between them. Recent advancements in sensing techniques have provided various ways to create human–machine interfaces, but they commonly come with different types of noise in the data collected from biosensors (electroencephalography, electromyography, electrooculography, etc.). Hence, implantable interfaces could collect physiological data with a high signal-to-noise ratio.

Another key challenge is to accurately model human intentions and cognition from the collected data and then give feedback to the robotic system. Progress in AI algorithms can help achieve collaborative analysis of multimodal physiological signals, facilitating the development of personalized rehabilitation training and intelligent assistance.

5.5. Telemedicine and Telesurgery

In the past, patients in rural areas who required complicated surgery needed to invite senior surgeons from other places to complete the operation, but in the future they will be able to quickly access high-quality healthcare via telemedicine and telesurgery. 5G technology, launched in commercial applications in 2019, has already demonstrated potential advantages in communication, with low delay, high speed, mass connectivity, and high reliability, enabling robotic systems for telemedicine and telesurgery to be used over long distances. Future advances in telemedicine and telesurgery could significantly reduce traveling costs for medical staff, alleviate the practical problem of the uneven distribution of medical resources in China, and benefit more patients in terms of quickly accessible and high-quality healthcare. Especially for telesurgery using 5G, through the use of virtual-reality or augmented-reality technologies, surgeons could complete long-distance surgery with an enhanced sense of immersion and without a sense of latency.

6. CONCLUSION

This review has provided an overview of the development of medical robotics in China. In terms of surgical robots, in addition to orthopedic and laparoscopic surgical robots, increased attention has been paid to transluminal endoscopic and interventional robotic systems, enabling minimally invasive surgery through natural orifices of the human body. For patients with physical impairment, research efforts have led to advances in various types of exoskeletons, prostheses, training robots, and mobile assistive robots, which can perform intelligent rehabilitation training or provide personalized assistance in daily life. To achieve accurate diagnosis and target therapy, extensive interventional diagnosis and treatment robotic systems have been studied. In addition, service robots have begun to play a significant role in hospital automation, in areas ranging from nursing and critical care to disinfection and logistics. Although domestic medical robots have made great progress, China still faces many emerging challenges, both technical and translational, as outlined above. However, the scope of new development and international collaboration is significant in terms of moving toward the next generation of medical robots.

FUTURE ISSUES

1. Robotic systems for endoluminal intervention with micro- and nanorobotics can be explored to achieve early, accurate, and intracavitary diagnosis and treatment.
2. Advanced micro- and nanorobotic systems will facilitate applications for targeted drug delivery and release and minimally invasive diagnosis and treatment.
3. For soft exoskeletons, research efforts need to focus on developing variable-stiffness materials and dexterous structures and on investigating precise control algorithms based on accurate modeling of kinematics and dynamics.
4. Intelligent human–robot interaction could be enabled by incorporating implantable human–machine interfaces and advanced AI algorithms.

5. The use of telemedicine and telesurgery could help solve the problem of limited medical resources in rural parts of China.

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