electronics

Review

Development Status and Multilevel Classification Strategy of Medical Robots

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Abstract: The combination of artificial intelligence technology and medical science has inspired the emergence of medical robots with novel functions that use new materials and have a neoteric appearance. However, the diversity of medical robots causes confusion regarding their classification. In this paper, we review the concepts pertinent to major classification methods and development status of medical robots. We survey the classification methods according to the appearance, function, and application of medical robots. The difficulties surrounding classification methods that arose are discussed, for example, (1) it is difficult to make a simple distinction among existing types of medical robots; (2) classification is important to provide sufficient applicability to the existing and upcoming medical robots; (3) future medical robots may destroy the stability of the classification framework. To solve these problems, we proposed an innovative multilevel classification strategy for medical robots. According to the main classification method, the medical robots were divided into four major categories—surgical, rehabilitation, medical assistant, and hospital service robots—and personalized classifications for each major category were proposed in secondary classifications. The technologies currently available or in development for surgical robots and rehabilitation robots are discussed with great emphasis. The technical preferences of surgical robots in the different departments and the rehabilitation robots in the variant application scenes are perceived, by which the necessity of further classification of the surgical robots and the rehabilitation robots is shown and the secondary classification strategy for surgical robots and rehabilitation robots is provided. Our results show that the distinctive features of surgical robots and rehabilitation robots can be highlighted and that the communication between professionals in the same and other fields can be improved.

Keywords: medical robots; multilevel classification strategy; development status; the necessity of secondary classification

Citation: Guo, Y.; Yang, Y.; Liu, Y.; Li, Q.; Cao, F.; Feng, M.; Wu, H.; Li, W.; Kang, Y. Development Status and Multilevel Classification Strategy of Medical Robots. *Electronics* **2021**, *10*, 1278. https://doi.org/10.3390/electronics10111278

Academic Editor: Paolo Visconti

Received: 10 April 2021
Accepted: 23 May 2021
Published: 27 May 2021

1. Introduction

Over the years, robotics and artificial intelligence (AI) have been introduced into the daily lives of most of the world's human population. Among the breakthrough technologies that have enabled the development of new medical devices, medical robotics is one of the most successful examples [1]. Medical robots have been utilized in multiple areas to assist humans with tasks that are repetitive, carry significant risk or require specific precision or some form of sophisticated complex ability. Novel usages for medical robots are found and described regularly [2]. During the evolution of medical care, the great advantages of medical robots have been confirmed in clinical diagnosis [3], surgical treatment [4], postoperative rehabilitation [5], home care [6], and other fields. Medical robots will certainly become increasingly important over the next few years [7,8]. In a way, medical robots have been integrated into every aspect of human life, and research and innovation of medical robots continues to develop various medical robots with different design purposes, applications, structures, materials, and intelligence levels.

1.1. Exploration in Medical Institutions

Robotic devices with medical auxiliary functions are now widely used in most medical institutions. Surgical robots, having been applied in medical institutions, have brought great breakthroughs for the medical industry. The first published robot in human surgery was in 1985 for a brain biopsy using a computed tomography (CT) image and stereotactic frame [9,10]. A few decades later, ROBODOC [11,12], which was developed by Computer Motion (Santa Barbara, CA, USA), was integrated with computer-aided technology by the Integrated Surgical Systems (ISS) company (Champaign, IL, USA) AESOP [13] for use in orthopedics; the ZEUS robotic system [14–18] was developed by Computer Motion and applied in internal medicine; and Da Vinci robot systems Standard (1999), S (2006), Si (2009), and Si-e (2010) [19,20] were developed by Intuitive Surgical for other medical departments.

Besides benefiting from the technological innovation, so-called "service robots" are used to serve medical staff and patients and have developed significantly. Service robots in hospitals are highlighted because of their potential scientific, economic, and social expectations. Service robots help nurses to guide, transport, clean, inspect, monitor, and disinfect, providing an important service for patients. At present, obstacle avoidance strategies [21], interactive control strategies (voice or gesture) [22], and humanoid structure design [23] have become hotspots of development to better meet the needs of clinical and hospital services. With the help of technological innovation and research enthusiasm support, the development prospects for service robots are good.

1.2. Progress in Home Care

The rapidly growing population of elderly people and improvements in the quality of life have resulted in an increased need for home care robots in daily life. Up to now, the different types of home care robots have mainly provided assistance with daily tasks, monitoring behaviors and health, and providing companionship [24–26]. As prominent examples, Care-O-bot [27], Robot-Era Robots [28], Zora [29], Justo Cat [30], and PARO [31] have received excellent evaluations. A previous study reported that these robotic technologies make it easier to live alone and provide a relatively better quality of life for a longer time [32].

1.3. Novel Materials and Appearances

Ranging from professional service robots used for surgical, rehabilitation, or nursing purposes to personal robots for diagnostic, medical teaching, or entertaining use, medical robots are becoming ubiquitous. Nowadays, accounting for the cultural diversity in the personal background of people is of high importance for the designers of robotic devices [33]. Therefore, medical robots with different appearances, materials, and structures have been developed to perform different tasks to meet medical requirements and user preferences.

In minimally invasive surgery (MIS) applications, the soft medical robots that can navigate narrow gaps and move, deform, and interact with soft organs have high demand. Controllable stiffness, utilized in laparoscopic surgery and endoscopy, and a tactile sensor sleeve for soft manipulators have been developed to overcome limitations in lack of haptic feedback [34,35].

In home care, humanoid robots are more popular, while in clinical applications, structural stability is one of the necessary conditions for medical robots. The printed humanoid robot [36] can perform dancing and show human-like facial expressions to provide entertainment and assistance to children and elderly people. The Humanoid Robot NAO [37] can be used as a trainer in a memory program for elderly people with mild cognitive impairment. At present, in addition to the requirements of precision and function, researchers are gradually paying more attention to the appearance and materials used in the construction of medical robots.

1.4. Difficulties in Diversified Development of Medical Robots

The rapid progress in medicine is driven by a combination of technological improvements (motors, materials, and control theory), advances in medical imaging (higher resolutions, magnetic resonance imaging, and 3D ultrasound), and an increasing acceptance of robotic assistance. Nowadays, medical robotics are ubiquitous and relied upon in most professional and living environments. Medical robots with different types, functions, and shapes have been gradually manufactured as a result of vigorous research and development.

The characteristics and technical preferences of medical robots used in disparate fields to meet various demands differ widely. In general, more attention will be paid to the precision requirements of medical robots used in medical institutions, while it will lay more emphasis on the interactive capabilities and intelligence of medical robots used in home care. The proliferation of different types of medical robot makes it difficult to generalize technologies in a single field. If the medical robots applied in the same application field and equipped with identical technical requirements can be effectively classified, it will be conducive to discussion and technical innovation. Besides, due to the wide variety of medical robots, it is difficult for people, especially the general public, to effectively distinguish the categories of medical robots. The classification of medical robots can help people in various industries distinguish types of medical robot, and understand the characteristics and other information of the corresponding types of medical robots.

Researchers have proposed several classification methods according to personalized needs. To date, classification schemes have been proposed that take into account the usage scenario, appearance, control manner, and construction material used. However, it is difficult to find a method to meet the requirements for the general public and studies, which does not result in lower recognition and a failure of communication among experts and professionals. In practical terms, it also means that most of the existing classification methods are not conducive to technical exchanges in related fields and may affect the technical development of medical robots.

There is no doubt that a reasonable classification strategy for medical robots would not only help to identify the type of robot more effectively, but would add impetus to the development of robotics technology. The reason why we performed this research lies in the fact that, despite the growing popularity of medical robots, there are some defects in their classification. Given the creative and novel medical robots likely to be developed in the future, it is important to improve the applicability of the classification method to existing and upcoming technologies. To solve these classification problems, the present classification methods and corresponding defects are reviewed, after which an innovative classification strategy for medical robots is proposed. In addition, we review the development status of several medical robots, through which we highlight the necessity of the secondary classification of surgical robots and rehabilitation robots. On this basis, we provide secondary classifications for surgical robots and rehabilitation robots, by which distinctive features can be shown and the communication between researchers in that or other fields can be improved. The article is concluded by providing an outlook of recommendations for medical robots in the future.

2. Classification Strategies and Characteristics Analysis of Each Medical Robots

2.1. The Status of Classification

The international standard ISO 8373:2012 and the International Federation of Robotics classify service robotics depending on their field of application into personal service robots and professional service robots, and medical robots are classified as a type of professional robot [38–40]. At present, multiple classification strategies for medical robots have been proposed based on their appearance, application scenario, function, and departments to which they are applied. Some classification methods for medical robots are shown in Table 1.

Table 1. Classification methods proposed for medical robots.

Classification Principe	Classification Method	Advantages	Disadvantages
Sizes and shapes	Macro-robot Micro-robot Biological robot	(1) Easy to classify (2) Providing a satisfactory application to the present and the upcoming medical robots.	(1) Having poor applicability to medical robots with different functions and fields. (2) Rough classification.
Application scenarios and functions	Surgical Robot Rehabilitation Robot Hospital-service Robot	(1) Easy to classify (2) Easy to distinguish the type of medical robot.	(1) Failing to provide good applicability to the present and upcoming medical robot (2) Difficult to cover all the medical robots
Application scenarios	Surgical Robot Rehabilitation Robot Assistance Robot Medical service Robot	(1) Providing a satisfactory application to the present and the upcoming medical robots.	(1) Failing to apply to the present and upcoming medical robots (2) Difficult to distinguish the assistance robots and medical service robot
Functions/ Departments	Neurosurgery robot Cosmetic surgery robot Orthopedic robot Laparoscopic robot Vascular intrusive robot Auxiliary and Rehabilitation robot Capsule robot . . .	(1) Having a detailed classification (2) Easy to classify; (3) Having a good ability to the existing medical robots (4) Having an excellent distinguishability to medical robots with diverse functions	(1) Having a poor capacity to the new medical robot developed in the future (2) Providing a fragile classification framework

According to the shape and size, medical robots can be defined as macro-robots, micro-robots, and biological robots [41–43]. In this way, medical robots can be intuitively categorized by their appearance and this classification method has better applicability for medical robots at present and in the future. However, due to the lack of identification of usage scenarios and functions, the method has the defect of fuzziness and coarseness. Specific, medical robots with similar sizes may have personalized functions, while medical robots with the same function may be configured as disparate structures. It is a challenge to clearly distinguish medical robots from the functional perspective, which is not conducive to academic research, industrial classification, and technical exchanges in various fields.

In consideration of the application scenarios and functions, medical robots were categorized as surgical robots, rehabilitation robots, and hospital service robots, or in another system as surgical robots, rehabilitation robots, assistance robots, and medical service robots [44,45]. Although the usage and working field of medical robots can be recognized by individuals, it cannot comprehensively accommodate all types of existing medical robots. Besides, the subtle distinction between assistance robots and medical service robots also tends to confuse classification systems.

Some studies have proposed to divide medical robots according to hospital department and functional role into several categories including neurosurgery robots, cosmetic surgery robots, orthopedic robots, laparoscopic robots, vascular intrusive robots, auxiliary and rehabilitation robots, and capsule robots [10,46,47]. Compared to other methods, this manner is more detailed. Due to the excellent distinguishability of medical robots with diverse functions, the existing robots can be easily classified. However, when a new medical robot appears, the corresponding category may not exist. While it is easy to distinguish and classify the types of medical robots, the classification method may lead to a huge number of categories and have poor applicability for new forms and functions, which leads to a classification system with a large structure but weak stability.

In the development of medical robots, a variety of classification methods and strategies have been proposed. Based on the above summary, it can be concluded that there are three major problems with the present classification methods: (1) it is difficult to make a simple distinction among existing types of medical robot, because it would weaken the understanding and identification of medical robots and impede technical exchanges and communication among professionals and researchers; (2) it is not easy to develop a classification system for existing medical robots that will accommodate new medical robots with innovative functions or forms; and (3) the general classification framework of medical robots may be constantly regenerated due to the novel medical robots persistently created. Providing a relatively stable general classification framework is therefore significant.

2.2. Establishing the Principle of Classification

The evolution of intelligent medicine has led to great breakthroughs in the number and variety of medical robots, which is constantly increasing. Medical robots in each industry and field are characterized by a wide variety of complex functions. Therefore, simple differentiation and comprehensive coverage of the existing medical robots are major factors in determining the classification method. Moreover, the classification of newly generated medical robots and the stability of the classification framework are important when establishing the classification strategy. With the perspective of classifying existing and possible new medical robots in the future, the principles that should be followed in determining the new classification strategy are identified in this section.

2.2.1. Principle of Easy Identification

Medical robots have become commonplace in every aspect of life. When people discuss, communicate, encounter, or think about a medical robot, if they can state the category of the medical robot quickly, the communication time would be reduced, communication barriers would be avoided, and the understanding of the medical robot might be deepened. The characteristic of simple recognition is not only conducive to the public to distinguish between and identify medical robots, but can provide a bridge for communication between technicians, scholars, or staff in public institutions. If the distinction of disparate medicals robots can be readily found, the classification effect will be noticeably improved.

2.2.2. Principle of Excellent Application Ability

The classification strategy must apply to all existing medical robots in order to distinguish between them. Equipped with the ability to identify existing medical robots, the proposed classification strategy also needs to consider the potential robots of the future. To achieve universal applicability, the scenes, fields, and characteristics need to be considered in the process of determining classification strategy.

2.2.3. Principle of a Stable Classification System

When the emergence of new medical robots has a significant impact on the classification framework, obviously such a classification strategy is not ideal. Therefore, it is necessary to propose a classification strategy that can satisfy the medical robots in different situations as far as possible, so that the classification system can be effective for a long time.

2.3. Proposed Classification Strategy

Here, we propose a multilevel classification strategy that shown in Figure 1 and includes a main classification method and secondary classification method taking into account the department where the medical robot is applied, its functions, operators, and service objects in medical processes, and its deficiencies. The main classification method aims to distinguish medical robots in a coarse manner, while the purpose of the secondary classification method is to make a detailed classification according to the characteristics of the main categories obtained by the main classification method.

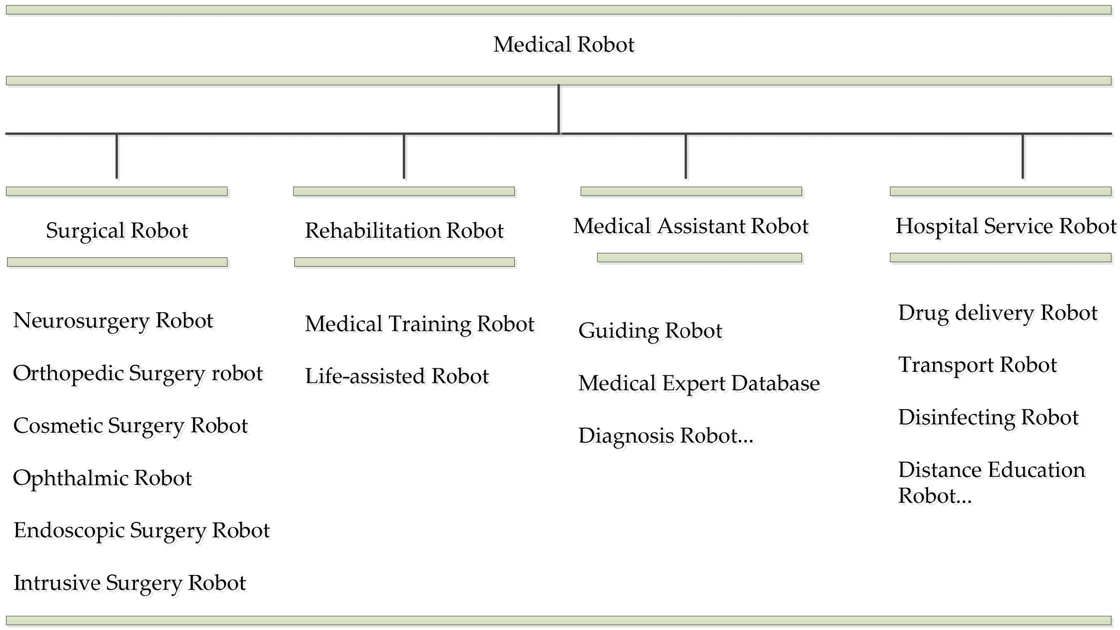

Figure 1. The proposed classification strategy in our paper.

In the main classification method, medical robots are classified into four main categories on the basis of their function and application field: surgical robots, rehabilitation robots, medical assistant robots, and hospital service robots. Surgical robots are used to assist surgeons performing operations. Rehabilitation robots play a role in improving conditions and are used to help patients with exercise and training. Medical assistance robots are usually applied to replace medical staff and provide a medical service, and hospital service robots are used to complete non-medical tasks in the hospital. In the secondary classification method, individual classifications can be carried out according to the characteristic information of each major category. We mainly review the development history of surgical robots and rehabilitation robots and summarize their subcategories.

The proposed multilevel classification strategy in our paper aims to cover almost all medical scenarios, by which the outstanding differences of medical robots are shown, and satisfactory applicability can be provided even when new medical robots arrive. Despite the wide variety of existing medical robots and the uncertainty of upcoming medical robots, our strategy possesses a basic and relatively stable ability to distinguish them.

3. Definition and Characteristics of the Main Types of Medical Robot

3.1. Surgical Robots

Surgical robots refer to medical robots that are routinely used in surgery and used as medical equipment in integrated disciplines such as medicine, mechanics, biomechanics, and computer science. The existing surgical robots offer increased dexterity to surgeons [48,49].

With the evolution of medical techniques and instrumentation, AI technologies such as computer vision technology, speech recognition technology, long-distance communication technology, and three-dimensional imaging technology are gradually being incorporated into the surgical robot system. Surgical robots that have emerged over recent years have reached a high level of accuracy and feasibility in minimally invasive surgery but have aroused widespread concern in the academic community [50–52]. At present, the main characteristics of surgical robots are as follows:

(a) Minimal invasion: The less invasive the surgical intervention, the greater the role of AI and the performance of specific tasks by medical robots [53]. Compared with traditional open surgery, one of the most significant advantages of surgical robots is fewer traumas, which can greatly reduce surgical wounds, shorten the recovery period of patients, and reduce the pain of patients.

(b) High precision: Generally, surgical robots are provided to serve surgeons and patients. As one of the most prominent factors, the accuracy of surgical robots will directly affect the health and safety of humans. In the clinic, it is imperative that the safety and stability of the surgical robot can be guaranteed. Compared with traditional surgery, surgical robots have improved accuracy.

(c) Wide range of surgical applications: due to the continuous optimization of driving and controlling manner, surgical robots are being selected by more and more departments in the hospital to perform surgical operations, resulting in an extensive increase of their application fields.

(d) High sensitivity: As an important index affecting the working range, the sensitivity of medical robots is selected to characterize the working ability. By integrating sensors at proper positions, the sensitivity of surgical robots would be improved.

3.2. Rehabilitation Robots

Rehabilitation robots refer to the devices that can automatically perform tasks to replace or assist certain functions of the human body, thereby playing a role in the rehabilitation process [54]. Rehabilitation robots currently play an important role in the functional reorganization and restoration, as well as metabolic compensation, of the nervous system, and the remission of muscle atrophy and joint atrophy. With the rapid expansion of intelligent control technology, network technology, simulation technology, and new material technology, the research and application of rehabilitation robots has increased the speed of the evolution process and accelerated the progress of related fields [55].

Rehabilitation robots need to be modified and optimized constantly to better meet the needs of patients. Compared with traditional methods, rehabilitation robots can drive patients for rehabilitation training with several advantages as follows:

(a) Single operation and strong repeatability: Rehabilitation robots (e.g., intelligent wheelchair, exoskeleton device, and training device) are often used to provide auxiliary services for disabled people. It is necessary for these processes to consume a large amount of time to execute simple and repetitive tasks and perform the set functions. Rehabilitation robots provide perfect training and service functions for strength, accuracy, and consistency in sports.

(b) Personalized training: taking into consideration the severity of the injury and duration required for the recovery process, personalized training can be performed, and individual features, modes, and structures of rehabilitation robots are required.

(c) High integration: A variety of sensors are usually integrated into rehabilitation robots with powerful information processing capabilities. By integrating sensors, kinematic and physiological data from patients can be recorded and measured during the process of rehabilitation training, and these data can be fed back to the robots in real-time so that the rehabilitation and training progress of patients can be quantitatively evaluated to provide the basis for surgeons to improve the treatment plan.

3.3. Medical Assistant Robots

Medical assistant robots are defined as robotic equipment, with patients as their service objects. They are used to substitute or support the hospital staff to perform medical transactions including examination, diagnosis, guidance, and disease analysis. The most prominent feature of medical assistant robots is that they replace nurses and physicians to provide diagnostic and treatment-related services to patients. Throughout the detection of disease and treatment, almost all operations related to medical procedures can be performed by medical assisted robots. Their use is not limited to hospitals, as they also have applications in daily life. At present, automatic medical diagnosis, monitor, health examinations, and other medical auxiliary work can be performed at home.

Medical assistant robots have been used to assist medical staff, and in aspects of diagnosis and examination, automatic diagnosis robots are popular. As a symbol of technological progress, capsule robots have revolutionized diagnostic procedures in the gastrointestinal tract by minimizing discomfort and trauma. A capsule endoscope robot called NaviCam™ [56] has been used in many medical examination centers. Previous research [57] proposed a magnetically actuated soft robotic capsule robot to improve their diagnostic accuracy for submucosal tumors or diseases. Another study [58] designed a novel capsule robot with the ability to move forward and backward, as well as turn, achieving the rendezvous and separation action through the three-dimensional rotating magnetic field.

During the outbreak of COVID-19, some hospitals recognized the significance of robots. Medical assistant robots were used to provide hospital guidance, intelligent triage, automatic diagnosis, business consultation, and other services.

With an increasing range of applications, the main characteristics of medical assistant robots used at medical institutions are reflected as follows:

(a) Professionalization: To perform specific medical operations, such as disease diagnosis, prediction, parametric analysis, and inspection, medical assistant robots are equipped with expertise and endowed with high accuracy to perform specific procedures. This means medical assistance robots can be designed to perform purpose-specific tasks to achieve assistance in various medical environments.

(b) Timeliness: During interactions with patients and doctors, it is necessary to quickly and accurately feedback the information required to improve the application experience. In the process of diagnosis and testing, a timely response can help patients and doctors get results as soon as possible, which reduces time costs, and means relevant treatment can be performed when necessary to avoid delays during illness.

(c) A rich library of experts: With their high degree of AI technology, medical assistant robots can detect health parameters, diagnose diseases, and provide rationalized suggestions by detecting the biological characteristics of patients. These all require the support of a strong expert database to provide intelligent diagnosis and treatment programs. During the application process, the professional knowledge and experience of the robot are also constantly being optimized and enriched.

3.4. Hospital Service Robots

Hospital service robots are robotic devices used in hospitals or other medical institutions to provide services unrelated to medical operations. Controlled by a particular person in medical institutions, hospital service robots are used to carry out ancillary tasks unrelated to medical operations such as transportation, disinfection, transfer, and cleaning. The usage of hospital service robots greatly enhances the service quality for patients and reduces costs for medical institutions.

The usage of hospital service robots can effectively relieve staff pressure and provide constant service on all days [59]. Besides, hospital service robots also help patients to take medicines by delivering medicines and supplies only at the assigned location. The HelpMate [60,61], which was developed by the American Transportation Association, can transport food and medicine in hospitals. The TimRob [62], developed by Shanghai TimRob Technology Co. Ltd. (Shanghai, China), provides services in nuclear medicine wards such as propaganda and education, physical examination, radiation measurement, item distribution, remote video, and environmental monitoring, etc.

Hospital service robots provide great assistance for medical staff and patients alike, and they generally have the following characteristics:

(a) Anthropomorphic appearance: to improve interactions with humans, hospital service robots are mostly designed as anthropomorphic structures, on the assumption that an attractive appearance will be favored by the public.

(b) Convenient movement: These robots must be developed to move in most scenarios while cleaning, disinfecting, transporting and transmitting. Flexible mobility is, therefore, a common characteristic of hospital service robots. Moreover, the easy-to-move feature can reduce the limitations of robot application scenarios.

(c) Easy to operate: The simple and convenient operation method reduces the learning time and adaptation time of the operator, and it makes it easier to be promoted and applied.

Both medical assistant robots and hospital service robots provide convenience to patients and medical staff. The significant difference between them lies in the usage purpose and the person who operates the robots. Medical assistant robots are used to provide auxiliary tools for medical processes, and the operators are professionals, such as surgeons and nurses in hospitals, or patients themselves. However, hospital service robots perform work unrelated to the medical process, and the operator is the specific staff member.

In summary, the characteristics and technical requirements of the different types of medical robot are dissimilar, which explains the separate research technological innovation for each. Therefore, the rational classification of medical robots can support the development of medical robots.

4. Development Status and Secondary Classification Strategy of Surgical Robots

The main classification strategy, a simple and intuitionistic classification method, is beneficial to distinguish between medical robots with different functions. For robots that belong to the same primary category, there are differences in their development direction, technical level, and usage characteristics, among other factors. Therefore, it is necessary to classify them further. Due to the rapid development progress of surgical and rehabilitation robots, we focus on their development status here, and highlight the necessity for secondary classification or reclassification.

4.1. Development Status of Surgical Robots

Presenting diverse characteristics, surgical robots with multifarious functions, structures, and materials are gradually being applied in the medical field. Currently, there are at least more than one hundred kinds of surgical robot, which are applied in different disciplines and configured as a variety of forms such as snakes, humanoids, and soft structures. Here, we summarize the current status of surgical robots according to their application department in the hospital and main function.

4.1.1. Neurosurgery

The main applications of surgical robots in neurosurgery are brain and spine surgery, for which the most advanced technologies at the forefront of research have been used. One of the typical applications is robotic surgery. Surgical robots can improve surgical outcomes through higher accuracy, shorter procedure duration, and lower costs [63,64]. The emergence of surgical robots makes it possible to locate a lesion, detect the boundaries of the lesion, select an appropriate surgical approach, and miniaturize the wound. As shown in Figure 2, in the 1980s, researchers completed the guided positioning of probes in brain tissue biopsies using the PUMA220 [9], which was the first time industrial robots were used for brain surgery. In 1987, the surgical robot system NeuroMate [65] was developed, the first FDA (Food and Drug Administration)-approved robotic device for neurosurgery, and MeumMate [66,67] was successively proposed and used in neurosurgery to guide the positioning of stereotactic surgery, creating a historic breakthrough in neurosurgery robots. In 1989, IMATRON in Japan realized the commercialization of the MeumMate. The surgical robots described above are multi-degree-of-freedom robot arms developed based on the industrial robot. Their disadvantages include relatively low accuracy and large volume or size.

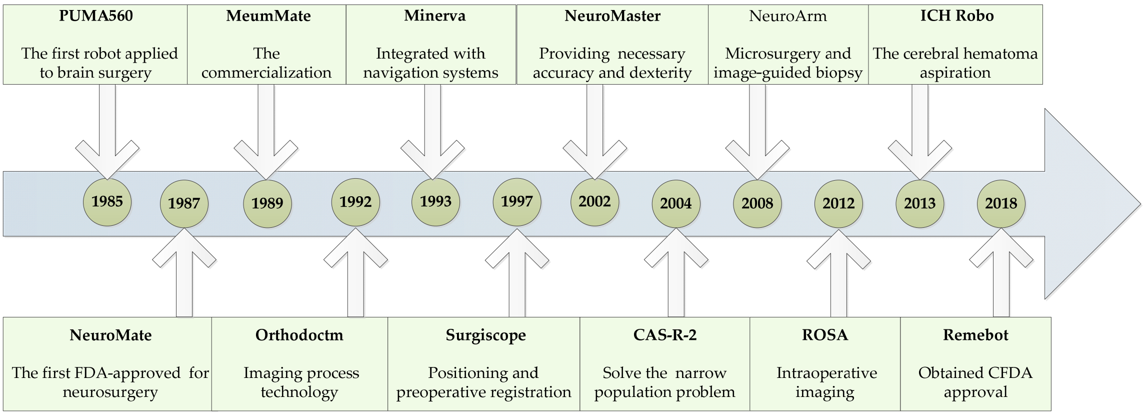

Figure 2. Timeline of a neurosurgical robot and relevant technology.

Since 1992, image processing systems and navigation systems have been gradually integrated into surgical operations. Accurate digital imaging has been used to open up new possibilities in image guidance [68]. The ISS company developed an image processing system named Orthodoctm [69], which initiated the era of surgical planning and surgical operations combined with medical imaging. In 1993, the first intraoperative imaging system, Minerva [70], was developed. In this system, a passive robotic arm can be moved in a preprogrammed direction to a specific site defined by an integrated navigation system. In 2008, NeuroArm [71] was developed by IMRIS in Canada, which is a system that involves both microsurgery and image-guided biopsy. In 2012, the robot system ROSA [72–74] incorporated intraoperative imaging into the workflow. The developments outlined here show that imaging systems in surgical robots have been continuously improved, and can now achieve real-time intraoperative display to assist surgeons in surgical operations.

Since 1997, frameless positioning technology has been gradually applied to surgical robots, and their volume, appearance, and registration technology have been gradually optimized. The surgical robot Surgiscope [75], which was developed by Elekta in Sweden, realized frameless positioning technology and preoperative MRI registration functions, through which the restrictions on intraoperative operators were reduced. In 2013, Germany developed a surgical robot called ICH Robo [76], which is a special robot for cerebral hematoma aspiration. The NeuroMaster [77–79], developed by the Robotics Institute of Beihang University, provides the necessary accuracy and dexterity of neurosurgical applications. With characteristics of accurate positioning and high surgical precision, CAS-R-2 [80], developed by HOZ medical, solved the problems of the narrow path in frame surgery. In 2018, the Remebot—developed by Remebot Technology Co., Ltd. (Beijing, China)—obtained CFDA (China Food and Drug Administration) medical device approval.

Surgical robots in neurosurgery have received more attention in terms of the development of intraoperative visual imaging technology, positioning technology, registration technology, and outstanding path selection technology.

4.1.2. Orthopedics

The application of surgical robots in orthopedics instigated the development of precision and minimally invasive orthopedic surgery. Further, the robots in orthopedics have received extensive and long-term attention. Since the mid-1990s, researchers have successively developed a variety of surgical robot systems used in orthopedics, which have been widely applied and promoted. The development timeline of orthopedic surgical robots is shown in Figure 3.

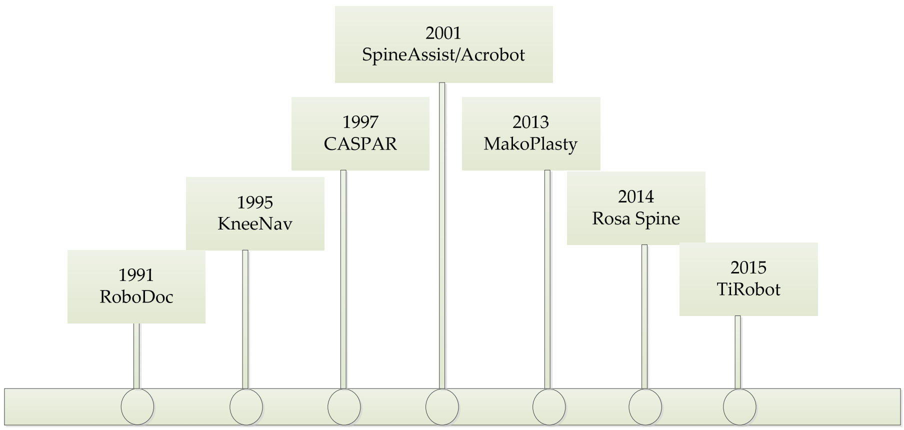

Figure 3. Timeline of typical orthopedic robots.

In 1991, ROBODOC [11,12]—an automatic robot system jointly developed by ISS and IBM—successfully replaced and revised bones and joints, and the outcome approached that of traditional surgery [81]. Subsequently, the robot system Acrobot [82] was proposed. As a collaborative and semi-autonomous robot system using preoperative CT imaging, Acrobot is the first to use the concept of active constraint, can safely and accurately operate in the surgical area, and significantly reduces iatrogenic damage [83]. In 1995, Carnegie Mellon University in the United States developed the HipNav system and the KneeNav system [84,85] for total hip replacement and knee replacement surgery, respectively. Both of them achieved three-dimensional (3D) planning method before surgery. In 1997, the Orto Maquet company in German developed the CASPAR robot system [86], which is a ROBODOC-like system used for skeletal grinding in total hip and total knee arthroplasty with a grinding accuracy of 0.10 mm, as well as for positioning of the tunnel entry-point of anterior cruciate ligament reconstruction. In 2001, SpineAssit [87,88], which is a small parallel spinal surgical robot with a height of less than 70 mm and mass of 200 g, was launched by MAZOR in Israel and was certified by the CFDA in August 2014. In 2013, the Stryker Corporation (Kalamazoo, MI, USA) acquired the Mako Surgical Therapy Company's machine-related technology. The main products of Mako include Mako plasty, which can accurately implant prostheses and restore natural hip and knee joints. In 2014, Medtech Medical (acquired by Zimmer Biomet in 2016) launched a surgical robot named ROSA Spine [89], which enables real-time breath tracking and compensation for intraoperative robots. Since then, ROSA Knee [90], ROSA One Brain [91], and ROSA One Spine have obtained the approval of FDA, meaning Zimmer Biomet was the first company to obtain FDA approval for robots operating on brain, spine, and knee in the surgical robot market. In 2015, the TiRobot [91,92] system, the first Chinese orthopedic robot system, was produced by a team composed of Beijing Jishuitan Hospital, Beihang University, and Beijing Tinavi Medical Technology Company (Beijing, China). In 2016, it became the first orthopedic robot to obtain CFDA approval.

Orthopedic surgical robots are responsible for key technical functions such as 3D image registration, visual positioning and tracking, and path planning. Orthopedic robots are constantly being optimized in the direction of miniaturization, increased precision, intraoperative real-time imaging, and improved three-dimensional perspective. To obtain better positioning accuracy, the patients' tissue is often fixed in an invasive manner during the operation, which increases the patients' pain and prolongs the recovery time of the operation. Therefore, while ensuring positioning accuracy, improving the fixation and registration methods to further reduce trauma is also an important direction of current research [93].

4.1.3. Endoscope

Surgical robots equipped with endoscopic technology are mainly used to gather internal information in cardiac, thoracic, hepatobiliary and pancreatic, gastrointestinal, urological, and gynecology surgery. In the traditional surgical operation, it is necessary to cut a sufficiently large wound so that the surgical tool can directly enter the target site, which results in a large trauma and difficult recovery. Compared with traditional surgical operations, the emergence of surgical robots can greatly reduce the pressure on surgeons by solving the above problems, and at the same time can improve surgery accuracy. Moreover, with the development of AI technology, surgical robot technology is also constantly being optimized.

The first commercial endoscopic surgical robot system was the AESOP1000 [94,95] developed by Computer Motion. In 1996, a voice control device was loaded into the endoscopic surgical robot system named AESOP2000 [13] (as shown in Figure 4) to realize speech recognition. Based on this system, researchers then successfully developed a surgical robot system named AESOP3000 [96] in 2003. The speech recognition system in AESOP3000 was improved, such that the manipulation of the robotic arm could be controlled by speech. This research provided a solid foundation for speech recognition and the speech control of surgical robots in endoscopy.

In early 2000, another surgical system developed by Computer Motion and used clinically was ZEUS [14–18]. This system obtained FDA approval in 2001 [97]. The famous "Lindbergh surgery" [98] was completed by the ZEUS. In 2001, the Intuitive Surgical Company (Norcross, GA, US) developed the world-renowned Da Vinci surgical robot system [99,100], as shown in Figure 5. The birth of the Da Vinci system was a milestone in robot-assisted management information systems. The Da Vinci system widely popularized robot-assisted management information systems in the medical establishment [101]. In 2004, the Johns Hopkins University in the United States developed a single-channel surgical robot called Snake-Like Robot [102], which was used to perform single-hole minimally invasive surgery. Having a smaller single-channel double-arm, a surgical robot similar to the Snake-Like Robot was developed by Columbia University in the United States in 2009 [103], and this had a higher integration level, and more flexibility and operability [104]. In 2010, the surgical robot system McroHand A [105], which is slightly smaller and has better flexibility than the da Vinci robot, was jointly developed by Tianjin University, Nankai University, and Tianjin Medical University General Hospital. In 2013, the minimally invasive surgical robot named Huaque-II [105] was developed by the Harbin Institute of Technology and this has greatly improved the safety and convenience of surgery, as it exceeded the range of observation of the human visual field.

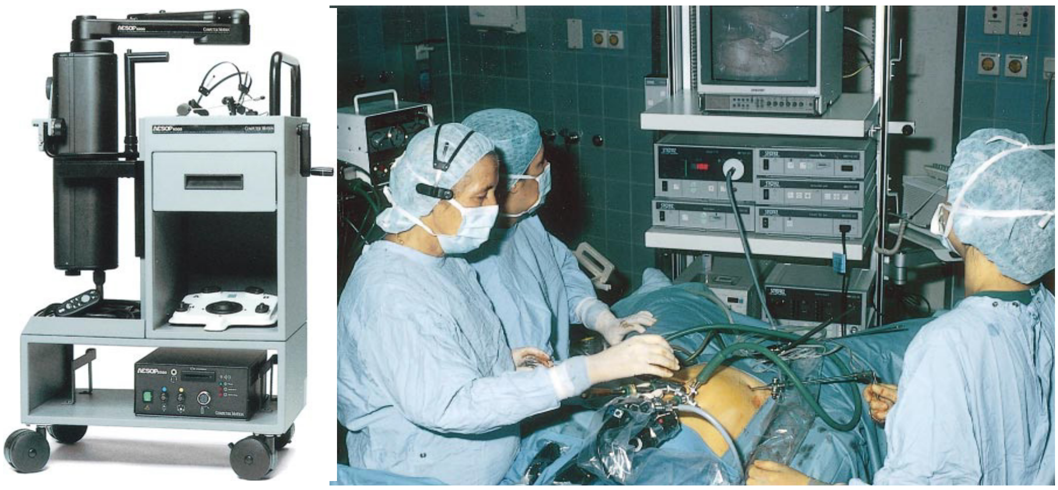

Figure 4. AESOP2000 and the endoscope surgery scene of using AESOP2000 (Computer Motion Company, Santa Barbara, CA, USA) [106].

Figure 5. The da Vinci surgical system (Intuitive Surgical, Inc., Sunnyvale, CA, USA) [102,104].

According to the development status of surgical robots with endoscopic technology, single-port surgical robots are one of the current research directions.

4.1.4. Intrusive Surgery

Cardiac surgery and neurosurgery are often intrusive. Guided by the digital silhouette angiography imaging system, vascular intrusive surgery is used to control the movement of the catheter in the blood vessel to achieve thrombolysis or the dilation of blood vessels. The use of vascular intrusive surgery robots has achieved reduced bleeding and trauma, improving safety and reliability. Compared with other surgical robots in neurosurgery and orthopedics, the research of vascular intrusive surgery robots started relatively late. Vascular intrusive surgery robots were developed in the 1980s. Our paper mainly reviews the development of the auxiliary intrusive system of magnetic navigation intrusive surgery robots.

In 1991, Ram et al. [107] reported that the first operation of the cardiac access for newborns had been performed by magnetic navigation technology. The earliest research institute that launched the magnetic navigation system was Stereotaxis in the United States, which developed the first-generation magnetic navigation system Telstar in 2002, followed by the second-generation magnetic navigation system Niobe [108], as shown in Figure 6, which integrated a digital imaging system that was developed based on Telstar. Magnetics, a company based in the United States, developed a catheter guidance control and imaging system [109], which can avoid interference with other medical equipment and the construction of unnecessary protection facilities, giving it some advantages over the Niobe system. In 2019, Zhao et al. developed a ferromagnetic soft continuum (FSC) robot [110] at the Massachusetts Institute of Technology in the United States. The FSC robot helps doctors to conduct rapid navigation and minimally invasive surgery for complex blood vessel networks using a remote control away from the radioactive source. In addition, Martel proposed a vascular intrusive robot using magnetic resonance fringe field navigation [111]. This robot can penetrate instruments with extremely small diameters into complex vascular structures that have not been accessible thus far using known methods, and success has been achieved in animal experiments.

According to the development trend of robots applied in vascular intrusive surgery, more attention is being paid to catheter drive technology, the catheter material, the anti-interference ability of robotic equipment, and thrombolytic technology, etc., which also suggests the surgery research trends and research hotspots for robots in the future.

Figure 6. The Niobe robot system (Stereotaxis, St. Louis, MO, USA; copyright is owned by Stereotaxis).

4.2. The Necessity of Secondary Classification of Surgical Robots

Based on the development trend of surgical robots in various hospital departments, on the one hand, it can be concluded that there is a slight gap in the research and development of surgical robots between countries. Encouraging relevant teams to speed up the localization of surgical robots is of great significance to improve overall medical levels and promote the development of advanced medical equipment. On the other hand, surgical robots applied to different departments in the hospital have their own unique characteristics, and there are great differences in the key techniques required for different operation types in different departments, and the overall structure of surgical robots therefore also differs.

To facilitate technical innovation and exchange among professionals in the same disciplinary fields, and to help people in other fields recognize surgical robots, it is necessary to provide a secondary classification capable of supporting accelerated development of surgical robot technology.

4.3. Secondary Classification Strategy for Surgical Robots

To date, surgical robots have been classified from the perspective of control methods, structural forms, and types of operation. However, these classification methods generally have problems of being too coarse or inconsistent.

According to the control method, surgical robots can be classified into passive, semi-autonomous, and fully autonomous surgical robots [112]. In practice, there is no strict restriction on the control strategy of surgical robots in each department. Thus, it is difficult to distinguish surgical robots from different departments and with functions according to the control method.

Depending on the type of surgery, surgical robots can be divided into microsurgery robots, minimally invasive robots, neurosurgery robots, and orthopedic surgery robots, etc. [113]. Among them, microsurgery robots and minimally invasive surgical robots can be applied to almost all departments, and most surgical robots are minimally invasive robots. Therefore, this classification method has the disadvantage of an overly fuzzy classification.

Some researchers have proposed other classification methods. For example, it has been suggested that surgical robots be divided into microsurgical and macrosurgical robots according to the size of machines, or alternatively, to be divided into nanosurgical robots, soft surgical robots, magnetic surgical robots, and capsule robots, etc., depending on the materials used to construct the robot. These classification methods generally also have the disadvantage of being too coarse and lacking the ability to distinguish between application departments in the hospital.

To distinguish the applicable departments and specific functions, we propose a secondary classification strategy for surgical robots. The main principle of the secondary classification strategy is to first distinguish surgical robots by the applicable departments, and then distinguish between surgical robots using similar technologies. Based on this, our paper divides surgical robots into neurosurgery robots, orthopedic surgery robots, cosmetic surgery robots, ophthalmic robots, endoscopic surgery robots, and intrusive surgery robots. In this system, the neurosurgery robots and orthopedic surgery robots are categorized by their department, while the endoscopic surgery robots and intrusive surgery robots are classified by their applied technology and instrumentation. Surgical robots that perform operations using endoscopes in thoracic surgery, gynecology surgery, and cardiac surgery are classified as endoscopic surgery robots, and the surgical robots involved in intrusive surgery in the neurovascular and cardiac surgery are classified as intrusive surgery robots.

By dividing surgical robots based on the hospital department in which they are applied, makes it easy to distinguish between surgical robots in different departments. It can also help ease communication between researchers in the same or different departments. Moreover, surgical robots performing vascular intrusive surgery and endoscopic surgery are uniformly classified as endoscopic surgery robots and intrusive surgery robots, helping to integrate the surgical robots in similar disciplines and facilitating communication between people in the corresponding disciplines.

5. Development Status and Secondary Classification Strategy of Rehabilitation Robots

5.1. Development Status of Rehabilitation Robots

Rehabilitation robotics is a vital branch of the medical robot and has become a research hotspot in the field. The research on rehabilitation robots includes many disciplines including rehabilitation medicine, biomechanics, mechanics, electronics, materials science, computer science, and robotics. The functions of rehabilitation robots are shown in Figure 7 in which the diversified functions are suggested. At present, rehabilitation robots are mainly used in medical institutions and homes to perform rehabilitation training and home care for patients.

5.1.1. Rehabilitation Training Scene

With regard to rehabilitation and training, the breakthrough came with the MIT-MANUS [114], which was developed by the Massachusetts Institute of Technology in 1991. The MIT-MANUS can realize the functional rehabilitation training of the arm, shoulder joint, and elbow joint in stroke patients. The Massachusetts Institute of Technology then developed a three-degrees-of-freedom wrist rehabilitation robot, hand functional rehabilitation robot, and other upper limb rehabilitation robot systems based on the MIT-MANUS. The typical product of the lower limb functional rehabilitation robot is LOKOMAT [115] launched by the Swiss Medical Device Company and the University of Zurich in Switzerland. Performing gait training for neurologic patients with gait disorders, the LOKOMAT is the first rehabilitation robot that was assisted by the lower limb gait correction drive device, a type of exoskeleton. REO, a lower limb rehabilitation robot system developed by Motorika Corporation in the United States, can induce patients to walk with the correct gait through repetitive training. The active and passive training for upper limbs or affected limbs can be remedied by the Mirror Image Movement Enabler [116,117], InMotion Arm Robot [118], the ARMEO Series Rehabilitation System [119], and the ReoGo Upper Limb Rehabilitation Robot [120]. In 2018, Fourier Intelligent independently developed an upper limb rehabilitation robot named Fourier M2, which was officially exported to the Barrow Neurological Institute in the United States. It is the first time that a rehabilitation robot has been awarded a license by the FDA and exported to the United States from China.

The limb function rehabilitation robot system in the rehabilitation training scenario has achieved certain results in clinical applications, but there are still some limitations including its complicated operation, high price, and lack of an active rehabilitation function.

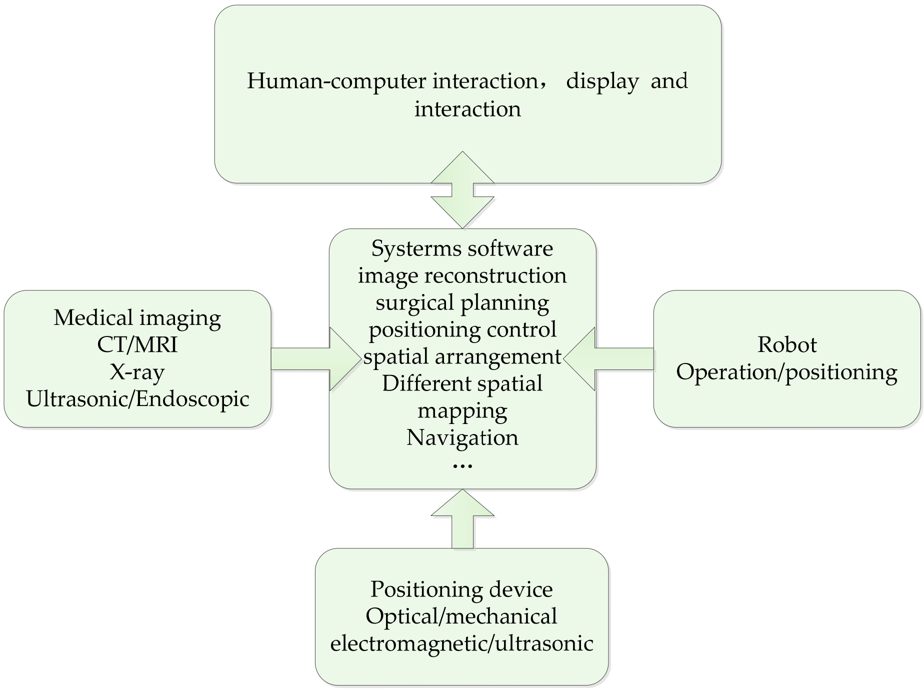

Figure 7. Function distribution diagram of rehabilitation robots.

5.1.2. Life Assisted Scenes

In terms of life assistance, the earliest commercialized rehabilitation robot was Handy1 [121], developed by the British Mike Topping Company in 1987. Handy1 can assist disabled patients with eating, visiting the toilet, and putting on makeup. In 2004, the Berkelev lower extremity exoskeleton was developed by the Ergonomics Laboratory of the University of California, Berkeley. In 2013, a rehabilitation robot named Exosuit was designed by Harvard University. The rehabilitation robot named MELKONG [122], developed by the Japan Institute of Mechanical Engineering, specializes in treating patients with mobility problems. Furthermore, Rewalk Robotics, the Israeli exoskeleton system provider, developed a wearable exoskeleton power device called Rewalk [123], which is the first exoskeleton product approved by the FDA. In 2004, the Chinese Academy of Sciences developed a lower extremity exoskeleton robot. In addition, different exoskeleton robots for various purposes have been developed by Harbin Institute of Technology, Shanghai University, and Zhejiang University [124,125]. The Illinois nursing robot with microcomputer control technology and intelligent detection technology developed by Illinois can automatically sense the excretion of patients and can be applied in diverse environments such as home care, medical institutions, and nursing homes, among others.

Over recent years, under the leadership of European and American countries, rehabilitation robots have achieved rapid development in the global market. Due to different usage scenarios and purposes of rehabilitation robots, there are also differences in the emphasis on the technological development of rehabilitation robots. To facilitate research and communication of the relevant technology, and to speed up development, it is necessary to further classify rehabilitation robots.

5.2. Secondary Classification Strategy for Rehabilitation Robots

In the development process of rehabilitation robots, researchers classified them according to the driving parts, training positions, among other methods. According to the driving part, rehabilitation robots can be divided into leg-driven robots, upper-limb driven robots, and sole-driven robots. According to the posture during training, rehabilitation robots can be divided into standing type robots, sitting type robots, and lying type robots. According to the combination method, they can be divided into embedded type robots and exoskeleton type robots [126,127]. According to the movement mode, they can be divided into fixed type robots and mobile type robots [128]. The scenarios and usage purposes of rehabilitation robots are not considered in the above classification methods. At the same time, the research focus and research direction of rehabilitation robots in various scenarios and purposes are different. Without considering the scenario and usage purposes, the secondary classification is not conducive to academic communication and technical exchanges between researchers in related disciplines.

From the perspective of scenarios and usage purposes, we divide rehabilitation robots into medical training rehabilitation robots and life-assisted rehabilitation robots. The medical training rehabilitation robot is used for physical function recovery and auxiliary exercises for patients. Medical training rehabilitation robots can help stroke patients recover their ability to actively control their limbs to a certain extent. Moreover, the existing medical training rehabilitation robot replaces some of the work of the therapist and can complete many tasks that cannot be performed by humans. It can also carry out functions of diagnosis and evaluation. However, medical training rehabilitation robots need to be used under the guidance of doctors, to achieve the medical purpose of the training and rehabilitation. Life-assisted rehabilitation robots can be used to assist or directly replace physical functions to help patients complete daily activities. For example, a wearable exoskeleton robot can help or replace walking for the patients, and the nursing robot can provide patients with daily feeding, applying makeup, and other nursing work. The life-assisted rehabilitation robot has a wide range of functions and can play a role in all aspects of everyday life.

The secondary classification strategy for rehabilitation robots proposed in our paper aims to clearly distinguish between application scenarios and usage purposes. When the further classification of rehabilitation training rehabilitation robots and life-assisted rehabilitation robots is needed, the above-mentioned classification methods by driving parts, mobile methods, and other methods can also be used. This additional classification will facilitate communication of technology researchers and academics in relation to rehabilitation robots in the medical field and life services.

6. Expectations and Outlook

The status we have reported reflects how medical robots have evolved over the last three decades. The emergence and usage of medical robots have led to increased convenience for surgical treatment, rehabilitation care, and other medical services, reducing the pressure on staff in relation to diagnosis and treatment, and facilitating the rehabilitation of patients. From the large-scale commercially available industrial manipulators to smaller, smarter, and custom-designed manipulators for specific clinical applications, the evolution of medical robots shows a great change in technological power. Further developments for medical robots will be achieved in the future. We consider the prospects for medical robots from the perspectives of security, low cost, and clinical needs.

6.1. Security

For a long time, precision medicine has been an important standard for medical robots and clinical medicine. Safety is the first condition for precision medicine. When a doctor performs a long and complicated operation, the accuracy of the operation is difficult to guarantee. Surgical accidents are usually caused by psychological or physiological problems of doctors. The emergence of medical robots effectively solves these problems. The fundamental purpose of medical robots is to serve patients and improve the safety, convenience, and effective services for doctors and patients. With the advancement of science and technology, more accurate and intelligent medical robots will appear, and it is a constant demand to increase the safety or the accuracy of operations and reduce the pain for patients.

6.2. Low Cost

With increasing demand for minimally invasive, efficient, and high-quality clinical services, and the continuous penetration of the concept of robots in popular cognitive concepts, the acceptance of medical robots will gradually increase. However, the medical robots currently used in medical institutions mainly rely on imports from developed countries, and the high cost has restricted the promotion and application of medical robots. At the same time, the price of medical robots will also affect the medical cost of patient treatment, increasing the burden on patients. If patients can get high-quality medical services at a lower medical service price, it will make the clinical application of medical robots further popularized.

6.3. Clinical Needs

To gradually optimize the clinical treatment, the most fundamental driving force comes from the clinical need to solve the pain points in the clinic. During the development process of medical robots, the service scope and the degree of intelligence are increased, while the operational risks continue to decrease. These are derived from the actual problems that need to be solved in clinical practice. Therefore, clinical needs will be the foundation of the development of medical robots. In the development process, in the future, various difficulties and problems will be faced, but the most fundamental driving force must be the needs of the patients and/or clinical medicine. Through technical innovation, it is widely believed that medical robots will soon be developed with a simpler structure, increased safety, and lower cost, and the application scope of medical robots will be more extensive.

7. Conclusions

Given that there are many types of robot in existence and no perfect classification method has been formed, here, we provided an overview of the classification of existing medical robots and provided a multi-level classification strategy in which the macro application scenarios are reflected in the main classification method and detailed individual information is reflected by the secondary classification method. In the main classification method, we divided medical robots into four major types: surgical robots, rehabilitation robots, medical assistant robots, and hospital service robots. The main classification method accommodates robotic devices used in various medical processes such as diagnosis, surgery, rehabilitation treatment, home care, auxiliary medicine, hospital services, etc. People can simply grasp the usage scenarios and purposes of surgical robots and rehabilitation robots. As for the confusing medical assistant robots and hospital service robots, we intend to distinguish them through the difference of performing transactions and the different service objects. Medical assistant robots are used to help doctors and nurses perform medical-related auxiliary work, such as auxiliary diagnostic robots, guidance robots, etc., while hospital service robots are used in medical institutions that are not related to medical action, such as disinfection, transportation robots, etc. Based on the main classification method, people can intuitively understand the functions from the name of the medical robots. Considering that the same type of medical robots may have different technical preferences, characteristics, and purposes, we provide a secondary classification method for surgical robots and rehabilitation robots according to the summary of the development status of surgical robots and rehabilitation robots. In the secondary classification method, individual classifications can be made according to the characteristic information of each major type. We classified surgical robots by the department and technical preferences into neurosurgery robots, orthopedic surgery robots, cosmetic surgery robots, ophthalmic robots, endoscopic surgery robots, and intrusive surgery robots, etc.; and we divided the rehabilitation robots into medical training robots and life-assisted rehabilitation robots. The secondary classification strategies for surgical robots and rehabilitation robots were proposed to facilitate communication between technical personnel in the corresponding fields. As for hospital service robots and medical auxiliary robots, we can clearly distinguish them by the operator and service object, and further distinguish them by their function. Thus, secondary classification methods for hospital service robots were not analyzed in this paper.

A reasonable classification method for medical robots not only delineates the categories of medical robots effectively but also promotes future development. We propose the multilevel classification strategy, aims to standardize the category of medical robot, boost the communication and technology development in each field. It is understandable that this classification strategy is novel, even though it uses some of the previously used type names. Although the classification method in our article is not very innovative, the proposed method can clearly distinguish all kinds of medical robots and be universally applicable to the future medical robots in future, which is the main significance of the basic principles of medical robot classification. The multilevel classification strategy proposed in this paper aims to comprehensively summarize the types of medical robots and facilitate communication between practitioners in the same industry or different industries, thus contributing to the in-depth development of different technical directions.

Author Contributions: Conceptualization, Y.K. and Y.G.; formal analysis, H.W., M.F. and Q.L.; investigation, W.L. and Y.G., writing—original draft preparation, Y.G.; writing—review and editing, Y.G., Y.Y. and Y.L.; project administration, Y.G., F.C. and Y.Y.; funding acquisition, Y.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Research Development Fund at the Natural Science Foundation of Guangdong Province, China, Grant Number 2019A1515011382, and the General Program of National Natural Science Foundation of China, grant number 62071311.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: We are grateful for the support of the Engineering Research Centre of Medical Imaging and Intelligent Analysis, Ministry of Education at Northeastern University, Shenyang, China, and the Medical Device Innovation Center of Shenzhen Technology University, Shenzhen, China.

Conflicts of Interest: The authors declare no conflict of interest.

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