Applications and Advances of Medical Robots in Surgery and Rehabilitation

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Abstract. Robots have become the mode of a growing signal of dealing with medical issues across the globe. The paper is a review of surgical and rehab robotics and offers a thorough overview of technological advancements and uses in clinical practice. The surgical robot section summarizes the processes by which these systems promote results of surgical operations through high accuracy in control and minimally invasive procedures, summarizes the clinical benefits that have been reported by these systems, and addresses future developments and future directions of automated systems. In the case of rehabilitation robotics, researchers evaluated the effectiveness of upper- and lower-limb exoskeletal systems in people with functional impairments with a particular focus on the critical importance of machine-learning algorithms to personalizing therapeutic interventions and evaluating training progress. The article also recognizes technical constraints and high costs as one of the major obstacles to increased use of medical robotics. It, therefore, proposes future endeavors to be directed at improving system acumen at minimized cost. The ultimate aim of the analysis will be to clarify how relevant robotic technology is in surgery and rehabilitation, thus serving as a good resource on future studies, practice, and policy. Keywords: surgical robots, rehabilitation robots, artificial intelligence.

1 Introduction

Along with the development of artificial-intelligence technology, the integration of robots into clinical settings is becoming a commonplace event. The emergence of medical robots is altering traditional modes of delivery of healthcare services. An extreme poverty of medical resources in the face of growing demand, which is accelerated by demographic ageing and an increase in the management of chronic conditions, is becoming increasingly evident. According to a forecast from the American Association of Medical Colleges in 2024, the U.S. could be short 19,900 surgeons by 2036 [1]. This means people need to use more medical robots to help with resource issues. Medical robots can help make medical care more equal across cities and rural areas, as well as between various regions of the country. From an economic benefit perspective, although the initial investment in medical robots is high, the efficiency improvements and shortened hospital stays shown in long-term operations lead to

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a decline in overall medical costs, offering new paths for the sustainable development of medical systems. Currently, thousands of surgical robots are in clinical use worldwide, and the cumulative number of robots assisted surgeries has already reached tens of millions [2]. Medical robots are quickly moving from the experimental stage to clinical practice, becoming an important method to improve surgical quality and alleviate medical manpower shortages.

Among the many application areas of medical robots, surgical robots and rehabilitation robots are the two most prominent categories. Surgical robot systems use precise mechanical arms and advanced imaging technology to allow surgeons to perform more refined minimally invasive surgical operations, clearly reducing surgical trauma and patient recovery time [3]. In recent years, with the development of artificial intelligence technology, surgical robots are developing toward autonomy and intelligence, with some surgical tasks already completable under the robot's autonomous control, showing great development potential [4]. Rehabilitation robots focus on helping patients with motor function disorders recover their abilities, providing precise, repetitive task oriented training that significantly improves the efficiency of rehabilitation treatment [5]. In particular, the integration of machine learning algorithms into rehabilitation robot systems could help in the development of personalized rehabilitation programs and the monitoring of patients' real-time status. This has made an important contribution to the field of rehabilitative medicine. This article aims to review the latest research on medical robots in surgery and rehabilitation in a systematic way. The article will analyze these aspects. It will organize the technical framework of surgical robot systems, their performance in clinical use, and the latest development trends. Then, it will explore how rehabilitation robots help restore motor abilities, and their new uses in personalized treatment and machine learning algorithms. It studies the main problems of today's medical robot technology and predicts its future development directions. The article aims to provide researchers in the medical robot field with a comprehensive technical development framework and deepen the understanding of the current status and trends of medical robot technology.

2 Surgical Robots

Surgical robots mainly refer to intelligent mechanical systems used to assist surgical operations. Typical surgical robots adopt a master slave control architecture with a surgeon's console and patient side operating arms, equipped with high definition three dimensional endoscopic imaging and multi degree of freedom minimally invasive surgical instruments, allowing the operator to remotely control the mechanical arms and perform fine operations in narrow body cavities. Compared to traditional laparoscopic surgery, robot surgery has an intuitive control interface and instruments flexible like human wrists, making surgical operations more precise and stable while eliminating the effects of hand tremors [3].

The most famous clinical product is the da Vinci system from Intuitive Surgical in the United States, which obtained FDA approval in 2000 and pioneered the master slave multi arm surgical robot [4]. Clinical research shows that robot assisted surgery can achieve smaller incisions, less intraoperative bleeding, and faster recovery. For example, in a meta-analysis of 14,448 patients, robot surgery compared to open surgery reduced blood loss by about 50%, transfusion rates by 27%, hospital stays by nearly 70%, and 30 day complication rates by 64%. Robot surgery still has benefits over traditional laparoscopic minimally invasive surgery, such as less blood loss and fewer transfusions [2].

The earliest usage of surgical robots was in urology. Nowadays, their application has expanded to encompass numerous other disciplines, including neurosurgery, gynecology, cardiothoracic surgery, and general surgery. Robot-assisted colorectal surgery has many benefits for general surgery. This is especially true for surgeries that involve deep pelvic areas. The robot's multi-joint instruments make it easy to execute dissection, cutting, and anastomosis [6]. Robot systems are employed for heart and chest surgeries such as coronary artery bypass grafting and mitral valve repair. Surgeons can sew accurately even when the heart is beating because they can move very precisely [2]. In gynecological surgery, robot assisted hysterectomy and myomectomy result in significantly reduced postoperative pain and shortened hospital stays [6]. In neurosurgery, the stability and precision of surgical robots provide important support for skull base tumor resection and spinal surgery [2]. These clinical practices indicate that surgical robot technology is breaking through the limitations of single specialties and developing toward multi-disciplinary comprehensive applications, bringing minimally invasive surgery benefits to more patients.

But at the current stage, surgical robots are mostly auxiliary tools fully controlled by doctors, with the robots themselves lacking independent decision making ability and only executing instructions. However, with the integration of artificial intelligence, automation levels are gradually rising. A review of FDA approved surgical robots from 2015 to 2023 shows that 86% of systems are still at the lowest automation level, providing only instrument support at level one; only 6% reach level three with conditional automatic handling of partial tasks; very few integrate machine learning [7]. The orthopedic field is developing rapidly, with some robots able to automatically perform bone cutting according to preplanning, with doctors only supervising, embodying initial autonomy.

The development of autonomous surgical robots represents the forefront direction of surgical robot technology. In 2022, the STAR system developed by Johns Hopkins University successfully completed intestinal anastomosis surgery in animal experiments, with its suturing quality even surpassing that of experienced surgeons, showing the huge potential of autonomous surgical robots [8].

3 Rehabilitation Robots

Rehabilitation robots are systems designed for patient functional training and motor recovery, widely used in neurology and orthopedics rehabilitation and other fields. Their rise is closely related to aging and the high incidence of neurological diseases, as with the increase in the elderly population, strokes have become a major health threat, often leading to limb function impairments [9]. Paralyzed patients need long-term rehabilitation, and rehabilitation robots provide technical support for this, able to customize training according to individual conditions, ensuring standardized movements and repetitions, promoting neural remodeling and accelerating recovery.

Depending on the site of action, rehabilitation robots can be divided into upper limb rehabilitation robots, lower limb rehabilitation robots, and life assistive robots, among others [10]. A good example is the HandSOME robotic glove that enables the user to pick things using their fingers. This machine is used to develop fine motor skills [10]. The ARMin exoskeleton system is equipped with a great number of sensors, which allows observing muscular activity and joint kinematics in real-time. The assistance levels are adjusted to correspond with the patients' actual movements [9]. This kind of training makes sure that patients can accomplish their training tasks and stop being too passive because they depend too much on the robot. Some new upper limb rehabilitation robots also use virtual reality. Training interfaces and other games can make patients become more engaged [10]. Clinical research indicates that the motor functions of patients' upper limbs can be significantly enhanced when virtual reality is combined with robot rehabilitation training. This enhancement can remain for a while after the training ends [9].

There are two kinds of robots that assist people with lower limb rehabilitation: exoskeletons that help people walk and platforms that help people exercise their lower limbs. They help people with paralysis in their legs or trouble walking get better. The Lokomat lower limb robot and the ReWalk exoskeleton are two examples. They are capable of supporting a portion of the patient's bodily weight and facilitating the normal movement of the legs. This gives stroke or spinal cord injury people walking exercise that is like normal walking. The Lokomat system supports the complete body weight and assists walking for early rehab patients who can't stand at all. This makes sure that patients can safely conduct walking exercise. The system will slowly lower the amount of weight support as the rehabilitation goes on, and it will encourage the patient to take part. A systematic review and meta-analysis in 2025 summarized data from 12 randomized controlled trials involving 651 stroke patients. The final results indicated that, in comparison to traditional physical therapy, lower limb rehabilitation robot-assisted training could markedly enhance the motor function of patients' lower limbs and improve their abilities to walk independently and maintain balance [11].

Despite the fact that the advantages of rehabilitation support robots to a certain field such as the control of gaits, the current trend is marked by better functional outcomes, though those are yet to reach a significant scale. This finding highlights the usefulness of rehabilitation robots in the recovery lower-limb functions in stroke patients and creates a new rehabilitative approach. Further, specific studies have focused on the application of lower-limb rehabilitation robots into pediatric recovery, with promising findings showing the beneficial impact of these robots in gait training of children with cerebral palsy, making these also feasible across the entire population [10].

The patient assessment function in rehabilitation robot systems is another important research direction. Conventional rehabilitation assessment predominantly depends on the subjective evaluations of therapists and standardized tabular examinations. The machine learning-based evaluation method can pull out important information from the huge amount of motion data that rehabilitation robots collect and measure patients' motor performance in an objective way. Patients frequently employ compensatory motions during rehabilitation training to accomplish tasks, such as tilting the trunk forward rather than extending the shoulder joint. Even though these compensatory motions can help you finish activities for a short time, they don't help you get better in the long run.

Machine learning models can find these compensatory patterns and fix compensatory actions by giving patients real-time feedback or automatically changing training parameters. This makes the training effective [5]. Finally, there is a significant amount of clinical and scientific data that testifies to the effectiveness of rehabilitation robots, which can improve both the speed of training and functional outcomes.

4 Existing Limitations and Future Outlook

Although medical robot technology has made significant progress in the past few years, it still faces many challenges in promotion and application. First is the high cost, whether purchasing surgical robot systems or rehabilitation exoskeleton devices, both require large capital investments, and later equipment maintenance also needs consideration, affecting their popularization in grassroots hospitals and rehabilitation centers [3].

At the same time, there are acceptance issues, and secondly, acceptance problems. Surgeons need long-term training to proficiently use surgical robots, hindering promotion [6]. Research shows that for surgeons to reach proficient operation of surgical robots, they usually need to complete dozens of surgeries, with the specific number depending on the complexity of the surgery type [6]. In the initial learning stage, surgery time is often longer, and complication risks may increase, making some experienced surgeons hold reservations about adopting new technologies. In the rehabilitation field, therapists and patients hold cautious attitudes toward new technologies, some personnel worry whether robots will replace manual treatment, while patients may feel uncomfortable with the equipment, needing time to adjust concepts [12]. In fact, the design intention of rehabilitation robots is to assist rather than replace therapists. Their main role is to undertake repetitive physical labor, allowing therapists to invest more energy in high value work like plan formulation and psychological support. On the patient side, some elderly patients are afraid of psychological barriers toward mechanical equipment, worrying about equipment failure or improper operation leading to injury, this psychological barrier needs to be gradually alleviated through sufficient promotion and experience [10].

From a professional perspective, surgical robots are considered to have high costs, but long-term effects are not superior to traditional laparoscopy, with some randomized trials not finding obvious differences [3]. In the rehabilitation robot aspect, most research focuses on motor function disorders after stroke, with limited sample sizes, and different study conclusions sometimes contradict each other, lacking large scale evidence to prove the long-term effects of rehabilitation robots [12]. For example, some studies only focus on short term indicators like hospital stay time and complication rates, while ignoring assessments of long-term recovery effects and quality of life [3]. In addition, research rarely focuses on cost analysis, even if robot training can bring clinical benefits, if its cost benefit is not as good as traditional treatment, it is difficult to promote in medical systems [12]. From regulatory and ethical levels, the safety standards and assessment systems for medical robots are in the process of improvement. For example, issues like failure risks of surgical robots and privacy protection all pose higher requirements for relevant regulations [12]. These limitations make current medical robots in clinical applications still in the stage of exploration and improvement.

The development of medical robot technology will advance through enhancing intelligence levels and reducing costs, among other aspects. In the surgical robot field, by means of artificial intelligence algorithms, future surgical robots have hope to realize automation of partial surgery steps, like autonomous suturing and tissue segmentation technology, thereby lightening the burden on clinical workers [4]. In the long term, with the accumulation of algorithms and data, it is highly possible for surgical robots to fully autonomously execute specific tasks, but doctors responsible for decision making and supervision will still be the mainstream mode, thereby ensuring efficiency and safety [7].

Future rehabilitation robots, with their customized design are also an important trend. Future rehabilitation robots will pay more attention to lightweight and wearable design, customizing equipment according to patients' specific needs, which will provide continuous rehabilitation support for patients [9]. Home rehabilitation robots are another important development direction. Small and low-cost rehabilitation equipment can allow patients to perform rehabilitation training at home, through remote monitoring systems, therapists can understand patients' training situations in real time and adjust plans timely manner. This hospital and home continuous rehabilitation mode will significantly improve the coverage of rehabilitation services [10]. The Fit4MedRob plan initiated in Europe is precisely through large sample clinical trials to assess the effects and cost benefits of rehabilitation robots, providing data support for promoting rehabilitation robots into clinical practice [12]. Future rehabilitation robots will be more efficient and intelligent, able to provide comprehensive functional recovery plans for different disease populations.

5 Conclusion

This article systematically reviews the latest research progress in medical robots in the two major fields of surgery and rehabilitation, analyzing the current status of technical development, faced challenges, and future development directions.

In the surgical robot field, with da Vinci as the typical, master slave systems can reduce trauma and bleeding. When artificial intelligence is included, surgical robots can work more independently. Currently, robots are capable of performing certain surgical procedures individually. Operations are more accurate now that there are compact systems and the capacity to undertake surgery from a distance. Surgeons can conduct more difficult surgeries better and with fewer blunders. Additionally, this advancement facilitates remote operations. In communities with limited resources, this can facilitate access to high-quality healthcare.

Upper and lower limb rehabilitation robots are suitable for doing the same training repeatedly. For patients with spinal cord injuries and strokes, this facilitates the effective recovery of their functions. Techniques of machine-learning are used to produce individualized protocols of rehabilitation, and to track the patient progress in real time, which adds accuracy to rehabilitative interventions. However, the implementation of medical robotic technology across the board faces major setbacks such as the high cost nature of the technology and technical shortcomings that hinder its implementation. The way forward should be to improve the system intelligence and at the same time lower the cost.

These concerns should improve over time as technology gets better and more clinical data is gathered. More companies are joining the market and starting to make things on a massive scale. Therefore, the expenses associated with the acquisition and operation of medical robots should decrease gradually. Subsequently, more medical facilities can make use of these robots.

This article organizes medical robot technology in an orderly manner. It provides researchers and healthcare workers with a technical framework and application reference. Medical robots may become increasingly autonomous as AI technology continues to improve. This could be a fantastic way to help with the lack of medical supplies around the world.

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