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A Scoping Review Regarding Robots' Role in Disease Treatment

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Abstract: Robots are increasingly being integrated into disease treatment to perform a wide range of functions aimed at optimizing therapeutic outcomes. With the rapid advancement of science and technology, robots are undertaking increasingly complex tasks in medical interventions. For instance, robots achieve exact movements in minimally invasive surgery, minimizing damage to surrounding tissues. In chemotherapy, they enable accurate drug delivery, reducing dosage errors to the lowest possible levels. Driven by factors such as the emergence of novel diseases and the growing complexity of medical demands, the field of disease treatment continues to evolve, and robotic technologies are poised to address these dynamic challenges. This review synthesizes pertinent literature sourced from the Google Scholar database, aiming to achieve two primary objectives: to categorize distinct types of robotic systems utilized in disease management and to clarify their corresponding application contexts. The systematically organized data not only furnishes innovative insights for scientific researchers, but also provides evidence-based support for clinical practitioners in selecting technological solutions, while concurrently supplying empirical foundations for governmental formulation of medical technology development strategies.

Keywords: Robotic Therapy, Minimally Invasive Surgery, Drug Delivery

1. Introduction

Since the outbreak of the novel coronavirus (COVID-19), the disease treatment field has urgently demanded innovative approaches to enhance therapeutic efficacy and operational efficiency. [1,2] Traditional treatment modalities have increasingly revealed limitations in addressing complex conditions and large patient populations, characterized by insufficient precision and low efficiency,which hinder the rapid alleviation of patient suffering. Despite continuous advancements in medical technology, the growing prevalence of refractory diseases and heightened patient expectations for treatment quality have intensified the pressure on conventional therapeutic methods [3,4].

Over an extended period, robotics has been recognized as a powerful tool to augment treatment outcomes and efficiency, demonstrating immense potential in disease management. Robotic systems are capable of undertaking critical roles across various therapeutic scenarios. For instance, surgical robots assist physicians in performing intricate and delicate operations, significantly reducing surgical risks through unparalleled precision [5]. Rehabilitation robots, tailored to patients' specific conditions, autonomously generate highly personalized training regimens to address individual recovery needs [6].

Beyond surgical and rehabilitative applications, robotics has made remarkable contributions to other domains of disease treatment. In pharmaceutical interventions, medication-dispensing robots ensure the precise formulation of drugs, minimizing human errors and safeguarding patient safety[7]. In radiotherapy, robotic systems achieve enhanced positioning accuracy and superior dose control, effectively targeting cancerous cells while minimizing collateral damage to healthy tissues[8].

This review employs qualitative analysis of existing literature to comprehensively explore the roles of robotics in disease treatment, critically examining their application advantages and existing challenges. The findings not only facilitate the development of more advanced and clinically adaptable robotic technologies but also promote public understanding of their value and prospects in healthcare. This study holds significant implications for advancing the medical industry toward intelligent and high-efficiency paradigms by fostering acceptance and trust in novel medical technologies.

2. The application of robots in disease treatment

2.1. Surgical field

Technological advancements in robotic systems present significant potential for disease treatment, transforming healthcare delivery. Since the inception of robot-assisted surgery in 1985, noted for its enhanced flexibility and three-dimensional imaging, this technology has been integrated into various medical specialties and explored in new areas. In breast surgery, multi-port robot-assisted nipple-sparing mastectomy (rNSM) has demonstrated clinical efficacy, although challenges such as restricted workspace and collision risks with multi-arm platforms remain. The Da Vinci Single-Port (SP) robotic platform mitigates these challenges with its adaptable three-dimensional camera and collision-averse articulated arms [9].

Since the introduction of single-port endoscopic robotic systems, their advanced designs have expanded the scope of minimally invasive surgery. In urology, single-port robot-assisted radical prostatectomy utilizes articulating instruments for 360° maneuverability, enhancing neurovascular bundle preservation and reducing hospital stays compared to traditional multi-port methods. In neurosurgery, the minimally invasive surgical robot for intracerebral hemorrhage independently developed by Tongji Hospital of Huazhong University of Science and Technology has successfully completed animal experiments. This robot is capable of precisely puncturing and aspirating hematomas in complex intracranial environments. Through the integration of perception and intelligent control, it can effectively reduce damage to healthy brain tissues. Equipped with a "rigid-flexible-soft" puncture needle, the robot can autonomously plan the puncture path and sense the intracranial environment. The emergence of this minimally invasive surgical robot for intracerebral hemorrhage has undoubtedly opened up a brand-new avenue for the treatment of intracerebral hemorrhage.

2.2. Rehabilitation field

In rehabilitation therapy, robotic technology is driving a paradigm shift from traditional empirical approaches to data-driven precision rehabilitation. The Cable-Driven Upper Limb Rehabilitation Robot (CDULRR) system, leveraging a myoelectric controller based on muscle synergy theory and advanced control strategies, constructs a closed-loop rehabilitation framework encompassing "intent estimation, motion assistance, and performance evaluation." The system utilizes a four-motor cable transmission mechanism combined with a six-axis force sensor for real-time collection of surface electromyography (sEMG) signals from eight upper limb muscle groups and three-dimensional kinematic data. The sEMG signals are sampled at 1 kHz, and the force sensor accuracy satisfies rehabilitation training standards.

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Experimental studies involving eight healthy participants demonstrated that the muscle synergy-based controller significantly improved force estimation accuracy, reduced trajectory tracking errors, and enhanced interactive force control compared to controllers without muscle synergy considerations. Notably, the system extracts low-dimensional non-negative commands from muscle synergy matrices. It integrates integrates state-space models with admittance control strategies to achieve real-time three-dimensional human force estimation and continuous motion assistance. When detecting changes in a patient's movement intent, the system rapidly adjusts the robot's assistance force and motion trajectory. If a patient encounters difficulty in specific tasks, the system autonomously switches to more suitable training modes [10]. This intelligent control mechanism enhances the specificity and generalization capability of rehabilitation training, offering a more effective solution for upper limb functional recovery.

2.3. Medical supplies distribution

Robotic technology is transforming medical supply logistics. Autonomous delivery robots, utilizing LiDAR and path optimization, facilitate precise, contactless transport of pharmaceuticals and medical devices, enhancing infectious disease prevention. This method minimizes direct contact between healthcare workers and infection sources, thereby reducing transmission risks. Simultaneously, through IoT-based real-time monitoring systems, dynamic allocation of medical resources is achieved, substantially improving the response speed of critical supplies and providing robust support for pandemic response operations. Standardizing operational workflows propels the medical logistics system toward intelligent and unmanned evolution, offering a vital technological pathway for building a sustainable healthcare ecosystem.

3. Social impact

3.1. Medical efficiency and quality improvement

Robotic technology has significantly influenced patients, healthcare, precision diagnostics, and resource allocation in disease treatment, enhancing therapeutic outcomes for patients. For instance, data from Zhuhai Hospital of the Fifth Affiliated Hospital of Sun Yat-sen University demonstrated that the use of the "Da Vinci Surgical Robot" in tumor resection for a 71-year-old esophageal cancer patient resulted in an intraoperative blood loss of merely 30 ml, with the patient able to ambulate on the second postoperative day.

Robotics propels technological progress in the medical sector. Advanced simulators utilizing augmented reality (AR) and virtual reality (VR) offer surgeons enhanced virtual training environments, markedly increasing training efficacy. In precision diagnostics, the CT-based pulmonary nodule detection system within the United Imaging Intelligent Medical Imaging-Assisted Diagnosis System, deployed at Beijing Hospital of Traditional Chinese Medicine (Huairou Branch), facilitates the swift identification of micronodules as small as 1 mm. Rehabilitation therapy advancements are significant. BEAR H1, an exoskeletal robotic system engineered by MileBot Robot, employs sensors to monitor human motion and anticipate movement intentions.. Its integrated gait monitoring system and active-passive training modes promote natural walking gait training for patients with lower limb motor dysfunction, thereby improving rehabilitation efficacy.

The integration of these technologies not only reshapes healthcare service workflows but also reduces errors in critical diagnostic and therapeutic procedures to submillimeter and millimeter levels through standardized operations. This progress provides robust technical support for building a modern medical system characterized by efficiency and precision.

3.2. Reconstruction of medical resource layout

In medical resource allocation, leveraging high-speed networks such as 5G, surgeons can remotely control robots to perform complex procedures over distances spanning thousands of kilometers. For instance, the Second Affiliated Hospital of Xi'an Jiaotong University successfully conducted a remote robot-assisted surgery for a patient located 2,600 kilometers away, effectively mitigating regional disparities in medical resource distribution.

The "5G + Intelligent Hospital Logistics Robot" network project in Longgang District, encompassing six hospitals, has successfully implemented automated medical supply distribution. This advancement reduces the burden on medical staff, enabling a focus on more critical clinical duties.

These advancements exemplify how cutting-edge technologies not only address inequities in healthcare access but also optimize operational efficiency through systematic automation, laying a foundation for equitable and sustainable healthcare ecosystems.

3.3. Social and economic structure change

Robotic technology is reshaping the healthcare industry landscape at the socioeconomic structural transformation level through multidimensional pathways. In cost control, Shaobao Medical Technology (Shandong) Co., Ltd. developed a neurosurgical robot by independently innovating core components and foundational algorithms, achieving localization of critical parts. Benefiting from tax incentives such as super-deductions for R&D expenditures, the company has reduced development costs. Future mass production is expected to lower manufacturing and hospital procurement expenses, facilitating the decentralization of medical resources to grassroots communities.

The labor market demonstrates a dual substitution-creation effect. McKinsey & Company forecasts that by 2030, nearly 12 million Americans in declining occupations will require job transitions, with around 9 million potentially moving to emerging sectors. Clerical and production roles are at risk of automation, while demand is expected to rise in healthcare, technology, and transportation services due to advancements in AI, an aging population, and the growth of e-commerce.

Pharmaceutical innovation has experienced substantial evolution. Biocytogen utilizes large-fragment gene editing to develop RenMice™ (fully human antibody mice) and employs in vivo drug screening, anticipated to shorten the drug development timeline from more than ten years to 1–2 years.This expedited commercialization of innovative drugs has facilitated collaborations with numerous global pharmaceutical leaders. These advancements not only improve the cost-efficiency of medical services but also stimulate new economic growth, profoundly influencing employment trends and industrial frameworks.

3.4. Social cognitive reconstruction

At the level of societal cognitive reconstruction, robotic technology is reshaping the value systems and behavioral paradigms within the medical field through multidimensional integration.

In the physician-patient dynamic, the Kasumi Clinic in Hiroshima, Japan, employs AI-assisted diagnosis for cerebral aneurysms, utilizing MRI scans and AI-generated results for final diagnoses. Yuki Shimahara, CEO of LPIXEL, reports a 10% increase in cancer detection rates with AI integration, reflecting enhanced patient trust in AI diagnostics. In response to aging populations, a multimodal ankle rehabilitation robot, co-developed by Dr. Yu Pan's team at Beijing Tsinghua Changgung Hospital and Professor Hong Bo's team at Tsinghua University School of Medicine, has shown significant efficacy. This robot employs human-machine interaction and brain-computer interface (BCI) technologies, allowing patients to control ankle movements via neural signals.

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Following extensive training, neural functional remodeling occurs, with preliminary studies indicating that patients undergoing 20 days of intensive training experience notable improvements in foot drop and circumduction gait, thereby enhancing rehabilitation outcomes and reducing treatment duration.

In the domain of technology ethics education, the European Union has progressively translated ethical principles into legal frameworks since issuing the Ethics Guidelines for Trustworthy AI in 2019. The Artificial Intelligence Act, formally adopted in 2024, codifies ethical guidelines into binding legal obligations. It introduces risk-tiered governance, fundamental rights impact assessments, and mandates algorithmic impact evaluations for AI systems. Although specific AI interpretability assessment tools are not yet included in licensing exams for physicians in 17 EU member states, the growing use of AI in healthcare demands the incorporation of ethical education and technical training into medical curricula, a trend likely to be institutionalized. These advancements collectively redefine medical practices, blending technological innovation with ethical governance to align societal expectations with evolving healthcare paradigms.

3.5. Ethical and legal challenges

The rapid advancement of robotic medical technology has introduced significant ethical and legal challenges. In 2021, a patient with colon cancer in Florida, USA, sustained accidental injuries during a Da Vinci Surgical Robot-assisted procedure and later died from complications. The patient's family filed a lawsuit against the manufacturer, highlighting the complexity of liability determination in robotic surgery accidents. Concurrently, medical data security remains a critical concern. In 2015, Anthem, a US health insurer, experienced a cyberattack that compromised the personal data of around 80 million individuals, including names, birthdates, Social Security numbers, addresses, phone numbers, and partial medical IDs. Hackers infiltrated the database through phishing attacks disguised as internal personnel, triggering widespread public scrutiny, regulatory investigations, and legal actions against Anthem. This incident prompted the healthcare industry to reevaluate and strengthen data security protocols. Despite technological advancements in high-income regions, medical resource disparities persist. Leading institutions perform thousands of robotic resections, while low-income countries face adoption barriers due to cost and infrastructure. Global collaboration is crucial for ethical governance and equitable access to intelligent medicine.

4. Trend of future development

4.1. Technological dimension

Enhanced sensor sensitivity and resolution facilitate precise detection of microscopic tissue alterations and subtle physiological signals. The drive system utilizes advanced materials and bionic designs, resulting in a lightweight structure that significantly increases power density, thereby improving the operational flexibility of robotic arms and achieving submillimeter precision [11]. By integrating artificial intelligence, big data analytics, and cloud computing, the system leverages deep learning algorithms and augmented reality technologies to rapidly process multidimensional data, establish precise perceptual models, and assist surgeons in formulating personalized surgical plans. This integration markedly elevates procedural accuracy and reinforces real-time interactive feedback capabilities during operations.

4.2. Application dimension

Robotics are now integral to medicine. In neurosurgery and cardiovascular interventions, they enable precision lesion excisions and intravascular procedures. For rehabilitation, robotics facilitate personalized training. In oncology, they enhance tumor resection and participate in chemo- and radiotherapy. They also ensure targeted gene delivery in gene therapy.

Telemedicine robots using 5G provide remote specialist access, while homecare robots offer health monitoring and chronic disease management. This integration improves diagnostics and therapeutics, transforming healthcare accessibility and enabling comprehensive health management.

5. Conclusion

Robotics is revolutionizing disease treatment through surgical precision, reduced trauma, and enhanced rehabilitation, expediting patient recovery and improving outcomes. The widespread implementation of robotics in healthcare has substantial societal implications. Patients experience improved therapeutic outcomes, reduced recovery times, and enhanced quality of life. Robotics is driving technological advancements, transitioning healthcare towards intelligent and precise models. Telemedicine robots mitigate regional healthcare disparities, improving access to medical services. The future of robotics in disease treatment involves enhanced AI and big data integration, enabling precise diagnostic and therapeutic decisions. As technology matures and costs decrease, robot-assisted therapies are poised for global expansion, transforming healthcare and improving patient well-being.

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