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THE ROLE OF ROBOTICS AND AUTOMATION IN MODERN MEDICINE: A NARRATIVE REVIEW

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ABSTRACT The integration of robotics in healthcare settings is significant due to its potential to enhance patient outcomes, reduce human error, and streamline operations. These technologies have a broad range of applications, from surgical robots to automated diagnostic systems, that offer unprecedented precision and efficiency in medical procedures. Despite these advancements, there are notable gaps in the literature. Many studies focus on the technical capabilities and individual applications of robotic systems, but there is a lack of comprehensive reviews that examine their broader impact on healthcare delivery and patient care. Furthermore, the challenges and ethical considerations surrounding these technologies are often underexplored, leaving healthcare providers with limited guidance on best practices and implementation strategies. The purpose of this paper is to provide an extensive narrative review of the role of robotics and automation in modern medicine. By synthesizing existing research, this review aims to fill the identified gaps and offers a holistic view of the current state and the prospects of robotics in healthcare. Key areas of focus include historical developments, current applications, technological innovations, and the benefits and challenges associated with these advancements. From a clinician's perspective, the integration of robotics in healthcare holds transformative potential. It promises to augment the capabilities of healthcare professionals, leading to more accurate diagnoses, safer surgeries, and more effective rehabilitation. By understanding the full scope of these technologies, clinicians can better navigate the evolving landscape of modern medicine, which ultimately improves patient care and operational efficiency. This review serves as a critical resource for healthcare professionals, policymakers, and researchers, providing a comprehensive overview of how robotics and automation are revolutionizing the field of healthcare.

KEYWORDS : Surgical Robotics, AI in Healthcare, Rehabilitation Robots, Diagnostic Robots, Telemedicine, Medical Robotics Challenges, Medical Automation

INTRODUCTION

Robotics is an interdisciplinary field that integrates computer science, engineering, and technology to design, construct, and operate machines capable of performing complex tasks autonomously or semi-autonomously (Rao, 2023). Robots rely on fundamental components such as sensors that function as the robot's eyes and ears, giving information about its surroundings, which allow them to perceive their environment; actuators, which enable movement and interaction with objects; control systems, which govern their behavior; and artificial intelligence (AI), which enhances their decision-making and learning capabilities (Components of Robot - Javatpoint, n.d.). Over the past few decades, robotics has evolved from simple mechanical devices to sophisticated systems capable of executing intricate tasks with precision and autonomy, driven by advancements in AI, machine learning, materials science, and miniaturization of components (Licardo et al., 2024).

In the context of healthcare, the integration of robotics holds great potential, and offers the promise of improved patient care, enhanced clinical outcomes, and optimized operational efficiency. Robotic systems are increasingly being employed in various aspects of healthcare, including surgical procedures, rehabilitation therapies, diagnostics, and hospital logistics (Bohr & Memarzadeh, 2020). Their ability to perform precise and consistent actions makes them invaluable in surgeries requiring high precision, thereby enhancing patient safety and surgical outcomes. Rehabilitation robots provide consistent and tailored therapy sessions, aiding patients in regaining mobility and strength (Reinkensmeyer, 2013). In hospital settings, service robots assist with logistics, reducing the burden on healthcare staff and allowing them to focus more on patient care. Diagnostic robots, equipped with AI capabilities, can analyze medical images and data with high accuracy, facilitating early disease detection and personalized treatment plans (Deo & Anjankar, 2023).

Despite these advancements, the full potential of robotics in healthcare is yet to be realized. Significant challenges, such as high costs, technical limitations, and regulatory hurdles, need to be addressed to unlock the transformative power of these technologies. This review aims to provide a comprehensive narrative review of the current state of healthcare robotics, talking about the key advancements, discussing the challenges, and exploring future directions in the field.

We will begin by categorizing the different types of robots used in healthcare, and explaining their specific roles and functionalities. Following this, we will go into the various applications of these robots, supported by case studies and extensive citations from existing literature, showcasing the many benefits they offer. Next, we will explore how modern technologies such as AI and machine learning are enhancing the capabilities of healthcare robots, making them more adaptable and efficient.

Addressing the challenges and limitations faced by the field is crucial for developing strategies to overcome them. We will examine the financial, technical, and ethical issues that currently hinder the widespread adoption of robotics in healthcare. Finally, we will explore future directions, proposing innovative ideas and speculating on upcoming trends that could further transform the field. By the end of this review, we aim to offer a thorough understanding of healthcare robotics, from current applications to future possibilities, emphasizing their potential to revolutionize healthcare delivery and improve patient outcomes.

Methods

To provide a comprehensive narrative review on the role of robotics and automation in modern medicine, we conducted a literature search, primarily on PubMed. Additional searches were conducted on Google Scholar to ensure comprehensive coverage. We have also included reliable websites that talk about their specific products. The search strategy involved using a combination of keywords and phrases related to healthcare robotics. The search terms included "healthcare robotics", "medical automation", "robotic surgery", "rehabilitation robots", "service robots", "diagnostic robots", "AI in healthcare robotics" and "challenges in healthcare robotics". To ensure the relevance and quality of the articles reviewed, we applied specific inclusion and exclusion criteria. The inclusion criteria comprised articles available in full text, written in English, and related to the application of robotics in healthcare settings. We did not impose any date restrictions to capture the evolution of the field comprehensively. Conversely, the exclusion criteria involved articles not available in full text, non-English publications, and studies not directly related to healthcare robotics or automation. Our analysis aimed to highlight significant advancements, practical applications, and existing challenges, as well as to identify gaps in the literature and suggest areas for future research.

By following this systematic approach, we aimed to ensure that our review provides a thorough and balanced examination of the role of robotics and automation in modern medicine, offering valuable insights for researchers, practitioners, and policymakers in the healthcare field.

Delving Into The Depths: Unveiling Healthcare Robotics

In this section, we begin on a comprehensive exploration of the groundbreaking advancements and diverse applications of healthcare robotics. From the precision of surgical robots to the transformative potential of rehabilitation and service robots, we talk about the

different ways in which robotics is reshaping the landscape of modern healthcare. Keeping in mind both the technological innovation and real-world impact, we uncover the remarkable capabilities and emerging trends that are driving the evolution of healthcare robotics. We aim to review the intricacies and implications of these cutting-edge technologies, paving the way for a future where robotics plays an increasingly integral role in patient care and medical practice.

Exploring Surgical Robotics: Advancements in Precision Surgery

Surgical robots have transformed the landscape of modern surgery, offering unparalleled precision, dexterity, and control to surgeons. In this section, we will explore the evolution of surgical robots, highlighting key advancements and exemplary technologies that have paved the way to this remarkable engineering feat.

A surgical robot is a sophisticated medical device designed to assist surgeons in performing various surgical procedures with enhanced precision, control, and flexibility. These robots typically consist of robotic arms equipped with surgical instruments, controlled by a surgeon from a console. Surgical robots utilize advanced technologies such as robotic arms, high-definition cameras, and specialized software to enable minimally invasive surgeries, where small incisions are made and instruments are inserted into the body (Rivero-Moreno et al., 2023).

The journey of surgical robotics began in the 1980s with the introduction of the ARTHROBOT, the first documented surgical robot. Developed in Canada, the ARTHROBOT assisted surgeons in orthopedic procedures by positioning the patient's limbs, marking the dawn of robotic assistance in surgery. Damage to the hip joint from trauma or disease causes pain and limits movement, necessitating Total Hip Arthroplasty (THA), a procedure to replace the damaged hip with an artificial one. The artificial hip consists of an acetabular component and a femoral stem, which can be either cemented or cementless. A cementless stem, designed for bone growth into its porous surface, requires precise bone-implant conformity for successful surgery and recovery. Traditional cementless THA often achieves less than 30% conformity, leading to slow recovery and a shorter implant lifespan. To address this, robotic surgical systems were developed to carve precise cavities in the femur. ARTHROBOT, when attached to the patient's femur with a bone clamp, simplifies the registration process, reduces operational costs, and allows surgeons to control it directly, providing tactile feedback and maintaining surgical accuracy with a virtual hard wall at the boundary (Kwon et al., 2002).

Figure 1
Left – ORTHODOC – 3D planning workstation
Right – ROBODOC – Surgical assistant

In the late 1980s, ROBODOC, another significant advancement, emerged from Integrated Surgical Systems. The ROBODOC Surgical System comprises two key components: ORTHODOC a 3-D workstation for preoperative planning, and the ROBODOC Surgical Assistant, a computer-controlled robot for precise bone and joint preparation in total hip and knee arthroplasty surgeries (Figure 1). Preoperative planning with ORTHODOC involves converting a CT scan of the patient's joint into a 3-D virtual bone image, allowing the surgeon to select and position a prosthesis within this image. The ROBODOC Surgical Assistant then uses this plan to accurately mill the bone and joint to fit the implant (Liow et al., 2017).

The PROBOT Surgical Robot Around the same time, PROBOT was developed at Imperial College London, specifically designed for prostate surgery (Figure 2). As men age, they are at risk of developing

prostatomegaly, often treated with transurethral resection of the prostate (TURP), a complex and sometimes repetitive surgery. PROBOT, tested in both labs and on human subjects, has successfully performed prostate resections. The PROBOT system includes online imaging, 3D prostate model construction, a user-friendly surgeon-computer interface, a counterbalanced mounting frame, and a computer-controlled robot (Harris et al., 1997).
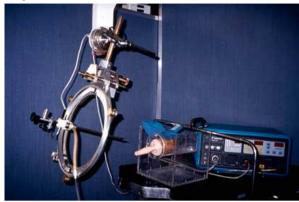

Figure 2

In the 1990s, Computer Motion introduced AESOP (Automated Endoscopic System for Optimal Positioning), a voice-activated endoscopic camera system that allowed surgeons to control the camera using voice commands (Figure 3). This innovation improved the efficiency and precision of minimally invasive surgeries by increasing accuracy and dexterity, reducing hand tremors, and adjusting movements or forces applied by the surgeon. Unlike systems requiring head stabilization for robot orientation, AESOP does not need any stabilization, making it advantageous for navigating probes or biopsy instruments. A video-assisted, voice-controlled robot has proven safe and efficient for endoscopic pituitary surgeries and is also a valuable training tool in teaching institutions. However, further research is needed to confirm its effectiveness in clinical settings, particularly regarding.

Figure 3
The AESOP Surgical Robot operative time, neurovascular injuries, and postoperative complications (Nathan et al., 2006).

A major leap in surgical robotics came with the development of the ZEUS robotic surgical system, also by Computer Motion (Figure 4). Telesurgery has proven viable, opening possibilities for surgeries in remote or difficult environments, such as war zones or space, and for collaboration with experts in humanitarian or teaching settings. On September 7, 2001, the first transcontinental robot-assisted laparoscopic cholecystectomy was performed. A surgeon in New York operated on a patient in Strasbourg via a high-speed connection, demonstrating the feasibility of telesurgery thanks to reliable robotization and data transfer. Until then, ZEUS surgeries were performed short-distance, with a hard-wired connection between the console and robotic arms. Long-distance surgery required a high-speed data transfer system to ensure image quality and minimal transmission delay. ZEUS enabled remote surgeries and was a precursor to the modern systems we see today (Pugin et al., 2011).

Figure4
Left – ZEUS Robotic arms
Right – ZEUS Console

The Da Vinci Surgical System represents the pinnacle of surgical robotics, combining advanced robotic technology with high-definition 3D vision and intuitive controls (Figure 5). This system allows surgeons to perform complex minimally invasive surgeries with great precision and control. It comprises a surgeon's console, a patient-side cart with four interactive robotic arms, and a high-definition 3D vision system. The surgeon operates from the console, manipulating the robotic arms and instruments with high accuracy, translating their hand movements into smaller, precise actions within the patient's body. This results in less trauma to the body, reduced blood loss, and quicker recovery times for patients. The system's enhanced visualization capabilities, including magnified 3D views of the surgical area, allow for better assessment and decision-making during procedures. The Da Vinci system has been widely adopted in various surgical disciplines, including urology, gynecology, cardiothoracic surgery, and general surgery, demonstrating its versatility and efficacy. Its success has set a new standard in surgical care, continually driving the development of more advanced and accessible robotic surgical technologies (UC Health, 2013).

Figure5
Left - Surgeon console
Middle – Patient cart with instruments
Right – The DaVinci Surgical Robot

The evolution of surgical robots from the early ARTHROBOT to the sophisticated Da Vinci Surgical System has dramatically transformed the landscape of surgery. These advancements have not only enhanced the precision and efficiency of surgical procedures but have also significantly improved patient outcomes, reducing recovery times and minimizing complications. As technology continues to advance, surgical robotics will undoubtedly play an increasingly vital role in modern healthcare, setting new benchmarks for surgical excellence.
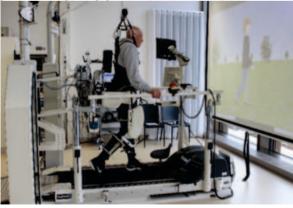
Revolutionizing Physical Therapy and Patient Recovery by Robotics
Rehabilitation robots are advanced devices designed to aid in the recovery of patients with physical impairments by providing repetitive, precise movements that facilitate the rehabilitation process. These robots assist in physical therapy by supporting, guiding, or resisting a patient's movements, thereby enhancing their strength, coordination, and mobility. Rehabilitation robots are often used in conjunction with human therapists to deliver comprehensive and personalized rehabilitation programs (Reinkensmeyer, 2013b).

Figure6

*The MIT-MANUS Robot for Shoulder Rehabilitation*Each year, around 700,000 Americans suffer strokes, ranking it as the third leading cause of death and the primary contributor to permanent disability in the U.S. Stroke-induced damage often results in hemiparesis, characterized by impaired motor control on the affected side. Recovery involves transitioning from flaccidity to increased muscle tone (spasticity), reduced muscle flexibility (contracture), and involuntary movement patterns (synkinesis). While complete recovery can be swift, partial recovery is more common and may take weeks to months. Rehabilitation programs aim to address these issues, with conventional therapy involving one-on-one sessions where therapists guide patients through repetitive exercises. The journey of rehabilitation robots began in the late 1980s with devices like the MIT-MANUS, developed at the Massachusetts Institute of Technology (Figure 6).

MIT-MANUS was an upper-limb robotic system designed to assist stroke patients in relearning motor skills by providing controlled, repetitive movements. This pioneering device demonstrated the potential of robotics in rehabilitation, leading to significant improvements in patient outcomes. Clinical trials have demonstrated the positive impact of robot-aided neuro-rehabilitation in reducing impairment, particularly at the shoulder and elbow, among both in-patient and out-patient populations (Krebs et al., 2007).

Figure7
*The LOKOMAT Rehabilitation Robot*During the 1990s, several innovative rehabilitation robots emerged. The LOKOMAT, developed by Hocoma, became one of the first commercially available robotic gait training systems (Figure 7). LOKOMAT is a widely used exoskeleton with linear drives at the hip and knee joints. It includes harness straps for body weight support, combined with a treadmill. The harness partially supports the patient's weight while the patient

supports the remainder. The treadmill assists patients in using their legs to mimic a normal gait. LOKOMAT replicates the biomechanics of lower limb walking and can be integrated with other technologies, such as augmented reality. Electric motors move the patient's knee and hip joints, and the device's lifting action induces passive ankle movements during the swing phase, which helps the patient's gait.

LOKOMAT assists body movement by matching the walking cycle, coordinating body parts and joints, and applying appropriate loads to each body part based on the kinematics of normal walking patterns (Rsaw, 2024).

Figure8
ARMin Rehabilitation Robot

Another significant advancement was the ARMin, an arm therapy robot developed by the Swiss Federal Institute of Technology Zurich (ETH Zurich). ARMin provided adaptive assistance for upper-limb rehabilitation (Figure 8). The extent of recovery post-stroke significantly depends on the severity and location of the lesion. However, only 18% of stroke survivors regain full motor function within six months. Restoring arm and hand functions is crucial for managing daily tasks and achieving independence. Exoskeleton robots like ARMin are better than end-effector-based robots, which connect to the human arm at a single distal point and cannot control individual joint torque across a wide range of motion, offering less guidance and support. ARMin provided adaptive assistance for upper-limb rehabilitation, allowing for a more personalized and effective therapy experience (Staubli et al., 2009).

Figure9
ReWalk rehabilitation motorized exoskeleton suit

Today, rehabilitation robots have evolved into sophisticated systems with advanced capabilities. The ReWalk is a motorized exoskeleton suit (Figure 9) designed to enable individuals with lower limb disabilities, including complete paralysis, to independently stand, walk, and in some cases, climb stairs. It includes a lightweight wearable brace support suit with motorized joints, rechargeable batteries, sensors, and a computer-based control system. It is worn around the legs, chest, and back, fitting closely over regular clothing. Patient stability while walking is aided by the use of crutches. It utilizes advanced motion sensors to detect the patient's upper body movements and shifts in gravity. These signals are processed by an onboard computer system, which initiates and maintains walking in the desired direction and at the appropriate speed. By keeping patients upright and exercising their paralyzed limbs daily, ReWalk can help solve health issues associated with long-term immobility, such as osteoporosis, pressure sores, and complications with the urinary, respiratory, cardiovascular, and digestive systems. ReWalk also serves as an alternative to other walking aids and standing devices, reducing the need for powered wheelchairs and the large vehicles required for their transport (ReWalk Robotics, n.d.).

Figure10
The EksoGT rehabilitation robot

Berkeley Bionics introduced eLEGS, later renamed Ekso, as a pneumatically powered exoskeleton designed to help paraplegics stand and walk using crutches or a walker. The device uses a computer interface with force and motion sensors to interpret and translate the user's gestures and movements into actions, enabling users to independently put on and take off the device, walk, turn, sit down, and stand up. Ekso weighs 45 pounds, has a maximum speed of 2 mph, and a battery life of 2-4 hours. The EksoGT (Figure 10) features adaptive algorithms that adjust the level of assistance based on the patient's progress, providing a personalized rehabilitation experience (Wikipedia contributors, 2024).

Rehabilitation robots have revolutionized the field of physical therapy, offering new hope and improved outcomes for patients with physical impairments. From the early MIT-Manus to modern exoskeletons like ReWalk and EksoGT, these technologies have significantly enhanced the rehabilitation process, providing patients with greater mobility, independence, and quality of life. As innovation continues to advance, rehabilitation robots will undoubtedly play an increasingly critical role in helping patients recover and regain their functional abilities.

Enhancing Hospital Operations: The Impact of Service Robots
The field of service robotics is relatively new, with a predicted demand for professional service robots in healthcare expected to reach $38 billion by 2022. These robots are set to reduce the workload of healthcare staff and assist in complex tasks. The first definition of a service robot, established by the Fraunhofer Institute in 1993, described it as a kinematic device that performs services semi- or fully automatically, not contributing to industrial manufacturing but performing useful work for humans and equipment. In healthcare, they are robots that carry out tasks either partially or fully autonomously in clinical settings. Service robots can make autonomous decisions based on sensor input, adapt to situations, and learn from past actions. Many are connected to cloud-based systems for storing user information and transaction data, enabling personalized service at a low cost through biometrics like face recognition (Holland et al., 2021).

The introduction of service robots in healthcare began in the 1990s with devices like HelpMate (Figure 11). The HelpMate trackless robotic hospital courier was initially designed by Transitions Research Corporation with NASA funding. The robot is battery-operated and uses advanced technology, including wireless radio and proprietary software, to guide its movements. It can transport up to 200 pounds of various items such as pharmaceuticals, lab specimens, equipment, meals, and medical records. It uses a laser scanner for obstacle detection, providing a 180º field of view and high reliability. It includes safety features like turn signals, emergency-stop buttons, and contact bumpers. A color touchscreen interface allows operators to easily send the robot to different locations within the hospital, and multiple robots can be centrally managed via a monitoring system. Its lockable compartments ensure secure deliveries, and its autonomous operation

allows hospital staff to focus more on patient care rather than logistical tasks. It has evolved significantly since its inception. It is now known as Pyxis HelpMate SecurePak. It is 4-foot-tall, 600-pound robot autonomously navigates hospitals without external guidance systems like tracks or wires (A Robot to Help **Figure 11** *The HelpMate robot*Make the Rounds | NASA Spinoff, n.d.).

Figure 11
The HelpMate robot

Figure 12
*The TUG robot*In the early 2000s, robots like TUG by Aethon started gaining traction. TUG robots (Figure 12) could autonomously navigate hospital corridors, delivering medications, lab samples, and meals to patients. These robots were equipped with advanced sensors and mapping technologies, allowing them to operate safely and efficiently in busy hospital environments (AITech.Studio, 2024).

Figure 13
The Moxi robot

Today, service robots have become more sophisticated and versatile. The Moxi robot (Figure 13), developed by Diligent Robotics, exemplifies the cutting edge of service robotics. Moxi is designed to assist with routine tasks such as fetching supplies, delivering lab samples, and distributing medications. Its advanced AI and machine learning capabilities allow it to learn from its environment and improve its performance over time (Ackerman, 2023).

Service robots have become an integral part of modern healthcare, revolutionizing hospital logistics and patient care. From the early HelpMate to advanced systems like Moxi, these robots have significantly improved operational efficiency, accuracy, and patient satisfaction. As technology continues to advance, service robots will play an increasingly vital role in healthcare, transforming the way hospitals operate and deliver care.

Enhancing Accuracy and Efficiency in Healthcare through Diagnostic Robots

Diagnostic robots are advanced systems designed to assist healthcare professionals in diagnosing diseases and medical conditions with greater accuracy and efficiency. These robots utilize AI, machine learning, and sophisticated sensors to analyze medical data, interpret diagnostic tests, and provide valuable insights. By supporting the diagnostic capabilities of clinicians, these robots help in early detection, precise diagnosis, and personalized treatment planning.

Figure 14
*The IDx-DR*In the 2010s, diagnostic robots advanced significantly with the introduction of systems like IDx-DR (Figure 14), the first FDA-approved AI-based diagnostic system for detecting diabetic retinopathy (DR). IDx-DR uses AI algorithms to analyze retinal images and identify signs of DR, providing accurate and timely diagnoses. Similarly, RetinaLyze is a cloud-based software designed for fundus image analysis, providing automated screening for DR, age-related macular degeneration, and glaucoma. As one of the earliest automated DR screening tools, it was first described over 15 years ago, utilizing lesion detection on 35 mm film images. Since then, it has been updated to meet current standards. The system processes fundus images submitted via a browser-based interface. The results are presented as the number of abnormalities detected in the image (Grzybowski & Brona, 2021).

Another milestone was the development of Arterys, an AI-powered platform that analyzes medical imaging data to assist in diagnosing cardiovascular conditions and cancers. Arterys leverages cloud computing and machine learning to provide real-time analysis and enhance diagnostic accuracy. CARDIO AI, LUNG AI, CHEST MSK AI, NEURO AI, and BREAST AI are the various modules of Arterys (Arterys | AMG-Medtech Ltd, n.d.).

Today, diagnostic robots have evolved into highly sophisticated systems. PathAI is a notable example, utilizing AI to analyze pathology slides and assist in diagnosing various cancers with high precision. PathAI conducted a study to identify potential biomarkers for immuno-oncology (I-O) therapy by analyzing the distribution patterns of CD8+ T cells within the tumor microenvironment (TME) using their AI-powered image analysis (IA) platform and gene expression profiling (GEP). The study focused on melanoma and squamous cell carcinoma of the head and neck, employing IA to quantify CD8+ T cells in various tumor regions such as the parenchyma, stroma, and invasive margins. The IA platform enabled precise mapping of T-cell infiltrates, revealing distinct patterns that could be categorized as immune desert, excluded, or inflamed. GEP was used to correlate these patterns with specific gene signatures. The high concordance between GEP scores and the geographic distribution of CD8+ T cells demonstrated the potential of combining IA and GEP to identify biomarkers that reflect the immune status of the TME and guide the use of I-O therapies (Szabo et al., 2019). PathAI's platform enhances the accuracy of pathological diagnoses and reduces the variability between different pathologists.

During our literature review, we found one very interesting paper on robotic telemedicine. This was regarding examining patients during the COVID-19 pandemic. The study developed a comprehensive clinical setup to assess the feasibility and acceptance of robotic telemedicine, focusing on feedback from both physicians and patients. The robotic-assisted cabin enabled various diagnostic tasks to be conducted remotely, significantly reducing the risk of COVID-19 cross-infection. Despite the spatial separation, physical interaction was maintained, enhancing examination capabilities. The implementation of advanced data transmission technologies, such as 5G, is crucial for bridging large distances in telemedicine, enabling real-time diagnostics. The study highlighted that while robotic and telemedical systems are well-received, their integration into clinical practice requires addressing several limitations, including patient selection bias and the need for technological simplifications for diverse age groups. Despite challenges like high initial costs and maintenance demands, the positive feedback suggests a promising future for robotic systems in telemedicine, potentially transforming healthcare delivery in rural, remote, and high-risk areas (Berlet et al., 2024).

Diagnostic robots have profoundly impacted healthcare by enhancing the accuracy and efficiency of medical diagnoses. From early systems to modern AI platforms like PathAI, these technologies have improved

the diagnostic process, leading to better patient outcomes. As diagnostic robotics continues to evolve, it will play an increasingly crucial role in healthcare, offering more precise, timely, and accessible diagnostic solutions.

Challenges And Limitations Of Healthcare Robotics
While healthcare robotics has brought about remarkable advancements, it is not without its challenges and limitations. Several notable examples highlight the complexities and setbacks faced by these technologies.

High Costs
The development, deployment, and maintenance of healthcare robots are often associated with substantial costs. For instance, the Da Vinci Surgical System, one of the most advanced surgical robots, can cost upwards of $1.5 million, with additional costs for maintenance and disposable instruments. These high expenses can be prohibitive, particularly for smaller healthcare facilities or those in resource-limited settings (Nelivigi, 2007).

Technical Challenges
Despite their sophistication, healthcare robots can encounter technical issues that impede their performance. One prominent example is IBM's Watson for Oncology. Initially heralded as a groundbreaking AI tool for cancer diagnosis and treatment recommendations, Watson for Oncology faced significant setbacks. Reports surfaced indicating that the system made inaccurate treatment recommendations and struggled to integrate the vast complexity of individual patient cases and evolving medical literature. These technical shortcomings showed the challenges of developing AI systems capable of reliably interpreting and applying medical information (Zou et al., 2020).

Similarly, Aidoc, an AI platform designed to enhance radiological diagnostics, encountered problems. While Aidoc's algorithms excelled in controlled environments, real-world applications revealed issues with false positives and missed diagnoses, raising concerns about the reliability and safety of relying solely on AI-driven diagnostic tools (Voter et al., 2021).

Regulatory And Ethical Concerns
The integration of robotics in healthcare brings forth significant regulatory and ethical challenges. Ensuring patient safety, maintaining data privacy, and establishing accountability in case of errors are critical concerns. The lack of standardized regulatory frameworks for healthcare robots can lead to inconsistencies in safety and efficacy standards. Ethical dilemmas also arise, such as decisions made by AI systems that could impact patient outcomes, raising questions about consent and trust in automated systems.

Integration Issues
Integrating robotics into existing healthcare systems can be challenging. Healthcare robots must seamlessly work alongside human healthcare professionals, electronic health records, and other medical devices. Cobots, or collaborative robots, offer a promising solution to integration challenges in healthcare settings. Unlike traditional industrial robots, cobots are designed to work alongside humans, assisting rather than replacing them. With built-in safety features like sensors and soft exteriors, cobots can operate in close proximity to healthcare professionals without posing significant risks. In healthcare, cobots can assist with tasks such as patient lifting and transportation, medication delivery, and repetitive manual tasks, thereby enhancing efficiency and reducing the physical strain on staff. Their user-friendly interfaces and intuitive operation make them easier to adopt and integrate into existing workflows. By leveraging cobots, healthcare systems can bridge the gap between human expertise and robotic assistance, ultimately improving patient care while addressing integration challenges (Weerarathna et al., 2023).

Moving Forward: The Need for Regulatory Bodies
Despite these challenges, the future of healthcare robotics remains promising. To address the issues of cost, technical reliability, and regulatory concerns, it is essential to establish comprehensive regulatory bodies dedicated to overseeing the development and implementation of healthcare robotics. These bodies could:

Set Standards: Develop and enforce standards for the safety, efficacy, and interoperability of healthcare robots.

Ensure Compliance: Monitor compliance with regulations and conduct regular evaluations of robotic systems in clinical settings.

Facilitate Innovation: Provide guidelines that balance innovation with patient safety, encouraging the development of advanced robotic technologies.

Promote Training: Support training programs for healthcare professionals to effectively integrate and utilize robotic systems.

By creating strict regulatory frameworks, we can streamline the adoption of healthcare robotics, ensuring these technologies are safe, reliable, and beneficial for patients and healthcare providers alike. With continued advancements and careful oversight, healthcare robotics has the potential to overcome its current limitations and transform the future of medical practice.

DISCUSSION
It is evident from the review that robotics is an interdisciplinary field, significantly enhancing various medical practices through the integration of computer science, engineering, and advanced technologies like AI. Over the past few decades, robotics in healthcare has evolved from rudimentary mechanical devices to highly sophisticated systems capable of performing intricate tasks with remarkable precision and autonomy.

The integration of robotics in healthcare is most prominently visible in surgical procedures. Surgical robots, such as the Da Vinci Surgical System, represent the pinnacle of these advancements. These systems offer unparalleled precision, dexterity, and control, enabling surgeons to perform minimally invasive surgeries with greater accuracy and reduced recovery times for patients. The evolution of surgical robots, starting from early systems like the ARTHROBOT and ROBODOC to advanced technologies like the ZEUS robotic surgical system, highlights the significant strides made in this field. These systems have not only improved the efficiency of surgical procedures but have also significantly enhanced patient outcomes by minimizing complications and reducing recovery times.

Rehabilitation robots are another critical application of robotics in healthcare, aiding in the recovery of patients with physical impairments. These robots provide repetitive, precise movements that facilitate the rehabilitation process, improving strength, coordination, and mobility. Early rehabilitation robots, such as the MIT-MANUS, demonstrated the potential of robotics in enhancing patient outcomes by providing controlled, repetitive movements. The development of systems like the LOKOMAT and ARMin further showcases the advancements in this field, offering personalized and effective therapy experiences that significantly aid in patient recovery.

Service robots in hospital settings assist with logistics, reducing the burden on healthcare staff and allowing them to focus more on patient care. These robots are designed to perform routine tasks such as delivering supplies, medications, and lab samples, thereby optimizing hospital operations and enhancing overall efficiency. The use of diagnostic robots, equipped with AI capabilities, further underscores the transformative potential of robotics in healthcare. These robots can analyze medical images and data with high accuracy, facilitating early disease detection and enabling personalized treatment plans, thereby improving patient outcomes.

Despite these advancements, the full potential of robotics in healthcare is yet to be realized. The adoption of these technologies faces several challenges, including high costs, technical limitations, and regulatory hurdles. The high costs associated with acquiring and maintaining advanced robotic systems can be a significant barrier for many healthcare institutions, particularly in developing regions. Technical limitations, such as the complexity of integrating robotic systems with existing medical infrastructure and the need for specialized training for healthcare professionals, also pose challenges to widespread adoption. Moreover, the regulatory landscape for healthcare robotics is complex and varies significantly across different regions. Regulatory bodies must balance the need to ensure patient safety with the need to foster innovation in this rapidly evolving field. The ethical considerations surrounding the use of robotics in healthcare, such as the potential for job displacement and the need to ensure patient privacy and data security, further complicate the adoption of these technologies.

The review also shows the transformative potential of AI and machine learning in enhancing the capabilities of healthcare robots. AI-driven

robotic systems can adapt to changing environments, learn from past experiences, and make informed decisions, thereby improving their efficiency and effectiveness in clinical settings. The integration of AI with robotics opens up new possibilities for personalized medicine, where treatment plans can be tailored to the specific needs of individual patients based on real-time data analysis.

Looking ahead, the future of robotics in healthcare appears promising, with ongoing research and development aimed at addressing the existing challenges and unlocking the full potential of these technologies. Innovations in materials science, AI, and machine learning are expected to drive further advancements in healthcare robotics, making these systems more accessible, affordable, and effective. The development of next-generation robotic systems that are more intuitive and user-friendly will likely enhance their adoption in clinical settings, enabling healthcare professionals to leverage these technologies to improve patient care.

CONCLUSION

In conclusion, the integration of robotics and automation in healthcare is revolutionizing the field, offering numerous benefits such as improved patient outcomes, enhanced clinical efficiency, and optimized operational workflows. The advancements in surgical robotics, rehabilitation robots, service robots, and diagnostic robots underscore the transformative potential of these technologies. However, addressing the challenges associated with high costs, technical limitations, and regulatory hurdles is crucial for realizing the full potential of robotics in healthcare. The future of healthcare robotics is bright, with ongoing innovations and research paving the way for more advanced, accessible, and effective robotic systems that will continue to enhance patient care and transform medical practice.

REFERENCES

1. *A robot to help make the rounds | NASA spinoff.* (n.d.). https://spinoff.nasa.gov/spinoff2003/hm_4.html
2. Ackerman, E. (2023, September 22). Moxi Prototype from Diligent Robotics Starts Helping Out in Hospitals. *IEEE Spectrum.* https://spectrum.ieee.org/moxi-prototype-from-diligent-robotics-starts-helping-out-in-hospitals
3. AITech.Studio. (2024, March 1). *Aethon TUG: Healthcare Logistics Robot | aitech.studio.* Aitech.Studio. https://aitech.studio/aip/aethon-tug/
4. *ARMin Rehabilitation Robot.* (n.d.). https://sms.hest.ethz.ch/. https://sms.hest.ethz.ch/research/current-research-projects/armin-robot/armin-v/_jcr_content/par/fullwidthimage/image.imageformat.1286.489673360.jpg
5. *Arterys | AMG-Medtech Ltd.* (n.d.). https://amg-medtech.com/arterys/
6. Berlet, M., Fuchtmann, J., Krumpholz, R., Naceri, A., Macari, D., Jähne-Schon, C., Haddadin, S., Friess, H., Feussner, H., & Wilhelm, D. (2024). Toward telemedical diagnostics—clinical evaluation of a robotic examination system for emergency patients. *Digital Health, 10.* https://doi.org/10.1177/20552076231225084
7. Bhattacharya, A. (2015, July 28). *The HelpMate robot.* https://i2.cdn.turner.com/money/dam/assets/150721050627-helpmate-robots-780x439.jpg
8. Bohr, A., & Memarzadeh, K. (2020). The rise of artificial intelligence in healthcare applications. In *Elsevier eBooks* (pp. 25–60). https://doi.org/10.1016/b978-0-12-818438-7.00002-2
9. *Components of Robot - javatpoint.* (n.d.). www.javatpoint.com. https://www.javatpoint.com/components-of-robot
10. Deo, N., & Anjankar, A. (2023). Artificial Intelligence with robotics in Healthcare: A Narrative review of its viability in India. *Curēus.* https://doi.org/10.7759/cureus.39416
11. Ganapati, P. (2009, September 11). *The PROBOT surgical robot.* https://www.wired.comhttps://www.wired.com/images_blogs/gadgetlab/2009/09/surgical_robots_1a.jpg
12. Gendreau, J., & D'Souza, M. (2019, November). *The Da Vinci Surgical system.* https://www.researchgate.net/. https://www.researchgate.net/publication/337063872/figure/fig1/AS:822405131927554@1573088071463/The-da-Vinci-Surgical-System-R-Intuitive-Surgical-Sunnyvale-California-robot-Image.png
13. Grzybowski, A., & Brona, P. (2021). Analysis and comparison of two artificial intelligence diabetic retinopathy screening algorithms in a pilot study: IDX-DR and Retinalyze. *Journal of Clinical Medicine, 10*(11), 2352. https://doi.org/10.3390/jcm10112352
14. Habash, R. (2019, February). *The IDX-DR.* https://millennialeye.com/. https://millennialeye.com/wp-content/uploads/sites/3/2019/02/Machine-Learning_IDx-DR.jpeg
15. Harris, S. J., Arambula-Cosio, F., Mei, Q., Hibberd, R. D., Davies, B. L., Wickham, J. E. A., Nathan, M. S., & Kundu, B. (1997). The Probot—an active robot for prostate resection. *Proceedings of the Institution of Mechanical Engineers. Part H, Journal of Engineering in Medicine, 211*(4), 317–325. https://doi.org/10.1243/0954411971534449
16. Holland, J., Kingston, L. M., McCarthy, C. T., Armstrong, E., O'Dwyer, P., Merz, F., & McConnell, M. (2021). Service robots in the healthcare sector. *Robotics, 10*(1), 47. https://doi.org/10.3390/robotics10010047
17. Jones, S. (2023, June 7). *The Moxi robot.* https://www.chla.org/. https://www.chla.org/sites/default/files/styles/16x9_two_thirds/public/2023-06/moxie-011-1024x683.jpg.webp?itok=kuB4J1nR
18. Krebs, H. I., Volpe, B. T., Williams, D., Celestino, J., Charles, S. K., Lynch, D., & Hogan, N. (2007). Robot-Aided neurorehabilitation: a robot for wrist rehabilitation. *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 15*(3), 327–335. https://doi.org/10.1109/tnsre.2007.903899
19. Krebs, H., Volpe, B., J Williams, D., Celestino, J., Charles, S., Lynch, D., & Hogan, N. (2007, September 17). *The MIT-MANUS.* https://www.semanticscholar.org/. https://www.semanticscholar.org/paper/Robot-Aided-Neurorehabilitation%3A-A-Robot-for-Wrist-Krebs-Volpe/d8c1447593ebc06b41ec647d363e8e7dd57d0fbd
20. Kwon, N. D., Yoon, N. Y., Lee, N. J., Ko, N. S., Huh, N. K., Chung, N. J., Park, N. Y., & Won, N. C. (2002, November 13). ARTHROBOT□ : a new surgical robot system for total hip arthroplasty. In *https://www.researchgate.net/.* Intelligent Robots and Systems. https://doi.org/10.1109/iros.2001.976319
21. Licardo, J. T., Domjan, M., & Orehovački, T. (2024). Intelligent Robotics—A systematic review of emerging technologies and trends. *Electronics, 13*(3), 542. https://doi.org/10.3390/electronics13030542
22. Liow, M. H. L., Chin, P. L., Pang, H. N., Tay, D. K. J., & Yeo, S. (2017). THINK surgical TSolution-One®(Robodoc) total knee arthroplasty. *SICOT-J, 3,* 63. https://doi.org/10.1051/sicotj/2017052
23. Marchal Crespo, L. (2016, June). *The LOKOMAT rehabilitation robot.* https://www.researchgate.net/. https://www.researchgate.net/profile/Laura-Marchal-Crespo/publication/305135632/figure/fig1/AS:946867890290690@1602762305790/The-Lokomat-Hocoma-AG-Switzerland-is-a-bilateral-gait-robotic-orthosis-that-is-used.png
24. Nathan, C., Chakradeo, V., Malhotra, K., D'Agostino, H., & Patwardhan, R. (2006). The Voice-Controlled Robotic Assist Scope Holder AESOP for the endoscopic approach to the SELLA. *Skull Base, 16*(03), 123–131. https://doi.org/10.1055/s-2006-939679
25. Nelivigi, G. G. (2007). Robotic surgery: India is not ready yet. *Indian Journal of Urology/Indian Journal of Urology, 23*(3), 240. https://doi.org/10.4103/0970-1591.33443
26. Pugin, F., Bucher, P., & Morel, P. (2011). History of robotic surgery□ : From AESOP® and ZEUS® to da Vinci®. *Journal of Visceral Surgery, 148*(5), e3–e8. https://doi.org/10.1016/j.jviscsurg.2011.04.007
27. Rao, R. (2023, July 14). *What is Robotics? A Comprehensive Guide to its Engineering Principles and Applications.* Wevolver. https://www.wevolver.com/article/what-is-robotics-a-comprehensive-guide-to-its-engineering-principles-and-applications
28. Reinkensmeyer, D. J. (2013a, November 26). *Rehabilitation robot | Definition, Types, & Facts.* Encyclopedia Britannica. https://www.britannica.com/technology/rehabilitation-robot
29. Reinkensmeyer, D. J. (2013b, November 26). *Rehabilitation robot | Definition, Types, & Facts.* Encyclopedia Britannica. https://www.britannica.com/technology/rehabilitation-robot
30. *ReWalk Robotics.* (n.d.). https://www.mossrehab.com/. https://www.mossrehab.com/rewalk
31. Rivero-Moreno, Y., Echevarria, S., Vidal-Valderrama, C., Stefano-Pianetti, L., Cordova-Guilarte, J., Navarro-Gonzalez, J., Acevedo-Rodríguez, J., Dorado-Avila, G., Osorio-Romero, L., Chavez-Campos, C., & Acero-Alvarracín, K. (2023). Robotic Surgery: A Comprehensive review of the literature and current trends. *Curēus.* https://doi.org/10.7759/cureus.42370
32. Rsaw. (2024, March 6). *Lokomat®, a Robot-Assisted Rehabilitation device, How does it help patients walk again?* Abdi Waluyo Hospital. https://abdiwaluyo.com/health-info/lokomat-a-robot-assisted-rehabilitation-device-how-does-it-help-patients-walk-again/
33. Simon, M. (2015, February 10). *TUG by Aethon.* https://www.wired.com/. https://media.wired.com/photos/5932842ef682204f73696681/master/w_1920,c_limit/tuggy-inline.jpg
34. Staubli, P., Nef, T., Klamroth-Marganska, V., & Riener, R. (2009). Effects of intensive arm training with the rehabilitation robot ARMin II in chronic stroke patients: four single-cases. *Journal of Neuroengineering and Rehabilitation, 6*(1). https://doi.org/10.1186/1743-0003-6-46
35. Szabo, P. M., Lee, G., Ely, S., Baxi, V., Pokkalla, H., Elliott, H., Wang, D., Glass, B., Kerner, J. K., Wapinski, I., Hedvat, C., Locke, D., Pandya, D., Adya, N., Qi, Z., Greenfield, A., Edwards, R., & Montalto, M. (2019). CD8+ T cells in tumor parenchyma and stroma by image analysis (IA) and gene expression profiling (GEP): Potential biomarkers for immuno-oncology (I-O) therapy. *Journal of Clinical Oncology, 37*(15_suppl), 2594. https://doi.org/10.1200/jco.2019.37.15_suppl.2594
36. *The EksoGT Rehabilitation robot.* (2010). https://robotsguide.com/. https://cdn.sanity.io/images/7p2whiua/production/9988abfd481db9a1aa66634353c6cb978cdd6acf-2048x1536.jpg?w=1400&auto=format
37. *The ROBODOC system including ORTHODOC.* (n.d.). https://www.researchgate.net/. https://www.researchgate.net/publication/235881 157/figure/fig1/AS:203146191216644@1425445234148/The-ROBODOC-system-including-ORTHODOC-a-3-dimensional-3D-preoperative-planning.png
38. UC Health. (2013, November 7). *About the DaVinci surgical system | UC Health.* https://www.uchealth.com/services/robotic-surgery/patient-information/davinci-surgical-system/
39. Voter, A., Larson, M., Garrett, J., & Yu, J. (2021). Diagnostic Accuracy and failure mode analysis of a deep learning algorithm for the detection of cervical spine fractures. *American Journal of Neuroradiology, 42*(8), 1550–1556. https://doi.org/10.3174/ajnr.a7179
40. W Holloway, R. (2009, August). *The AESOP surgical robot.* https://www.researchgate.net/. https://www.researchgate.net/profile/Robert-Holloway-3/publication/51437277/figure/fig2/AS:610718843928576@1522618127649/Computer-Motions-AESOP-Automatic-Endoscopic-System-for-Optimal-Positioning-has-allowed.png
41. Weerarathna, I. N., Raymond, D., & Luharia, A. (2023). Human-Robot Collaboration for Healthcare: A Narrative review. *Curēus.* https://doi.org/10.7759/cureus.49210
42. Whooley, S. (2020, December 30). *ReWalk Rehabilitation Motorized exoskeleton suit.* https://www.therobotreport.com/. https://www.therobotreport.com/wp-content/uploads/2020/12/ReWalk_pair.jpg
43. Wikipedia contributors. (2024, April 13). *Ekso Bionics.* Wikipedia. https://en.wikipedia.org/wiki/Ekso_Bionics
44. Winata, S. (2018, July). *Zeus Robotic Surgical System.* https://www.researchgate.net/. https://www.researchgate.net/profile/Stanley-Winata/publication/327561755/figure/fig3/AS:669403108634648@1536609546810/Zeus-Robotic-Surgical-System-1.jpg
45. Zou, F., Tang, Y., Liu, C., Ma, J., & Hu, C. (2020). Concordance Study between IBM Watson for Oncology and real clinical Practice for cervical cancer patients in China: A retrospective analysis. *Frontiers in Genetics, 11.* https://doi.org/10.3389/fgene.2020.00200