



Review

Innovative Robotic Technologies and Artificial Intelligence in Pharmacy and Medicine: Paving the Way for the Future of Health Care—A Review

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Abstract: The future of innovative robotic technologies and artificial intelligence (AI) in pharmacy and medicine is promising, with the potential to revolutionize various aspects of health care. These advances aim to increase efficiency, improve patient outcomes, and reduce costs while addressing pressing challenges such as personalized medicine and the need for more effective therapies. This review examines the major advances in robotics and AI in the pharmaceutical and medical fields, analyzing the advantages, obstacles, and potential implications for future health care. In addition, prominent organizations and research institutions leading the way in these technological advancements are highlighted, showcasing their pioneering efforts in creating and utilizing state-of-the-art robotic solutions in pharmacy and medicine. By thoroughly analyzing the current state of robotic technologies in health care and exploring the possibilities for further progress, this work aims to provide readers with a comprehensive understanding of the transformative power of robotics and AI in the evolution of the healthcare sector. Striking a balance between embracing technology and preserving the human touch, investing in R&D, and establishing regulatory frameworks within ethical guidelines will shape a future for robotics and AI systems. The future of pharmacy and medicine is in the seamless integration of robotics and AI systems to benefit patients and healthcare providers.

Keywords: innovative robotic technologies; artificial intelligence; pharmacy; medicine; health care



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1. Introduction

Progress in health care is not standing still. The rapid advancement of technology has transformed medicine as other industries. Robotic technologies and automation are playing an increasingly crucial role in the fields of pharmacy and medicine in an era where efficiency, accuracy, and personalized care are of utmost importance [1]. Innovations are driving the evolution of healthcare practices and shaping the industry's future by offering significant potential to improve patient care, streamline processes, and enhance overall efficiency [2].

AI and robotic technologies are transforming health care and medicine. AI helps healthcare providers make better decisions by providing them with comprehensive and personalized information about each patient [3]. This leads to more effective treatments and improved patient outcomes [3]. AI and robotics automate routine tasks, making healthcare delivery more efficient [4], helping to reduce costs and improve patient care [4]. AI and supercomputing are being used to accelerate the process of drug discovery and design [5]. This could lead to the development of new and more effective treatments [5]. Robotic process automation (RPA) in pharmacy is another area where these technologies are making a significant impact. RPA software automatically handles manual, repetitive, time-consuming, and highly structured tasks such as data entry and back-office functions [6].

Innovative robotic technologies have emerged as promising solutions [7–11] to address these challenges. They enable precision, accuracy, and automation across various aspects of pharmaceutical production, patient care, and medical interventions. As the global population continues to age and the demand for healthcare services surges, healthcare professionals and institutions face mounting challenges. These include limited resources, rising costs, and an increasing need for personalized care [12,13]. From drug manufacturing and quality control to telemedicine and robot-assisted surgery, the adoption of advanced robotic technologies is transforming the delivery of health care, paving the way for a more efficient, personalized, and patient-centric future [14,15].

In the following sections (Figure 1), we discuss the key innovations in robotic technologies across the pharmaceutical and medical sectors, examining their benefits, challenges, and potential implications for the future of health care. Furthermore, we spotlight notable companies and research institutions at the forefront of these technological breakthroughs, showcasing their groundbreaking work in developing and implementing cutting-edge robotic solutions in pharmacy and medicine.

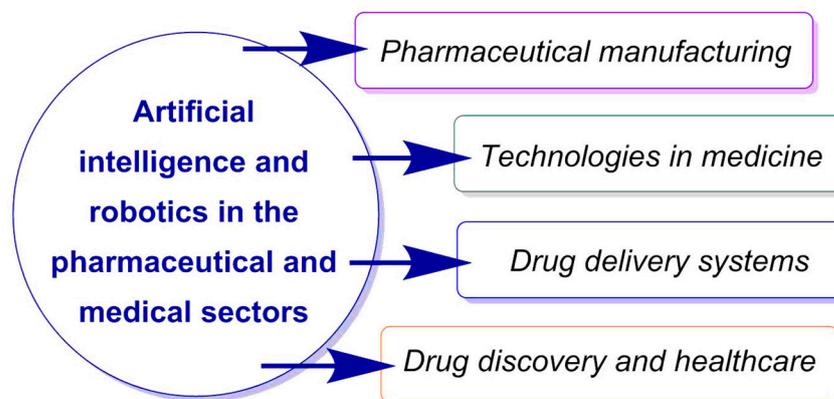


Figure 1. The key directions in robotic technologies applied in the pharmaceutical and medical sectors.

This work investigates the latest developments in innovative robotic technologies applied to pharmaceutical manufacturing, drug delivery, and medical procedures. Here, we highlight their impact on the healthcare landscape and discuss the potential implications for patients, healthcare professionals, and the global healthcare system.

2. Robotic Technologies in Pharmaceutical Manufacturing

Innovative robotic technologies are increasingly implemented in the pharmaceutical manufacturing industry. Pharmaceutical manufacturing has witnessed significant advancements in recent years, with robotic technologies playing an integral role in enhancing efficiency, precision, and cost-effectiveness. Some key areas where robotic technologies are utilized in this field are outlined as follows (Figure 2):

- *Automation of manufacturing processes:* Robots and automated systems are increasingly being used to perform a variety of tasks, including compounding, dosing, forming, and filling of medicinal products.
- *Automated mixing and dosing systems* allow for accurate dosing and mixing of drug components, which ensures product uniformity and reduces the risk of deviations from quality standards.
- *Packaging and labeling:* Robots can automatically package, label, and stack finished products, helping to increase efficiency and reduce labor costs.
- *Warehousing operations:* Robots can be used to automate the warehousing, shipping, and transportation processes of products, ensuring a high level of compliance and quality assurance.

- *High-speed sorting and analysis:* Robots can perform high-speed procedures such as component sorting or drug testing, increasing productivity and ensuring the accuracy of results.
- *Collaborative robots (cobots) in drug manufacturing:* Cobots work alongside human operators to perform tasks such as drug packaging and labeling, enhancing productivity while reducing the potential for errors.
- *Robotic quality control systems:* Advanced robotics and machine vision technologies are employed to inspect pharmaceutical products for defects, ensuring compliance with stringent quality standards and reducing the likelihood of product recalls. They can also monitor compliance of manufacturing processes with GMP (good manufacturing practice) standards.
- *3D printing of drugs:* The use of 3D printing in the field of drug production allows for the creation of personalized doses and forms of drugs that can take into account the individual needs of patients. Furthermore, 3D printing can help in the manufacture of complex tablet geometries, improving their solubility and bioavailability.

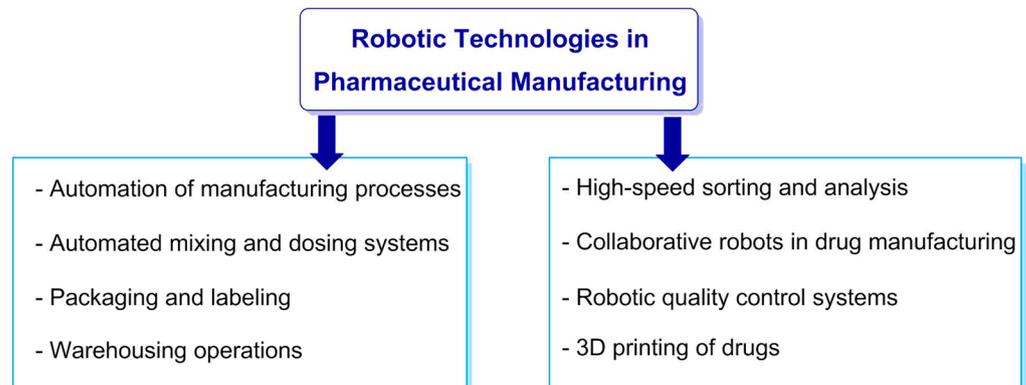


Figure 2. Directions of application of robotic technologies in pharmaceutical manufacturing.

These examples of innovative robotic technologies in the field of drug manufacturing illustrate the potential of automation and the implementation of the latest technologies to improve the efficiency, quality, and safety of drug production.

There are several leading companies developing and manufacturing innovative robotic technologies for drug manufacturing. Their technologies are designed to enhance productivity, reduce costs, and improve product quality by automating various aspects of the manufacturing process (Table 1).

Table 1. Leading companies and examples of their robotic solutions for the pharmaceutical industry.

Supplier Name, Country	Robotic Solutions for the Pharmaceutical Industry	Examples of Robotic Solutions
ABB Robotics, Switzerland	Robots are designed for tasks such as drug manufacturing, packaging, and quality control.	ABB’s FlexPicker robots [16–18] provide high-speed and precision handling for various pharmaceutical products. Its advanced vision system and software enable it to adapt quickly to different product shapes and sizes, making it suitable for a wide range of pharmaceutical manufacturing applications.
KUKA Robotics, Germany	Robots are utilized in various applications, such as drug manufacturing, assembly, and packaging.	The KR AGILUS robot (KUKA Robotics) series [19] is known for its speed, precision, and adaptability in handling delicate pharmaceutical products. Its advanced software and control systems allow for seamless integration with existing production lines and offer flexibility in programming for various tasks, such as drug manufacturing, assembly, and packaging.

Table 1. Cont.

Supplier Name, Country	Robotic Solutions for the Pharmaceutical Industry	Examples of Robotic Solutions
<i>FANUC Corporation, Japan</i>	Robots are used for tasks such as drug dispensing, packaging, and assembly.	FANUC's M-1iA robot series [20] is a family of high-speed, lightweight robots designed for the precision assembly and handling of small pharmaceutical components. These robots are equipped with FANUC's proprietary software and control systems, which enable them to perform complex tasks with high accuracy and efficiency.
<i>Universal Robots, Denmark</i>	Specializes in collaborative robots (cobots), which can be easily programmed and adapted for drug packaging, labeling, and quality control.	The UR series of cobots [21] are known for their ease of use, flexibility, and safety features. These cobots are equipped with intuitive software that allows for easy programming and adaptation for tasks such as drug packaging, labeling, and quality control.
<i>Stryker Corporation, USA</i>	Robotic systems are used for tasks like precision drug dispensing and product assembly, helping to ensure accuracy and reduce human error.	The Mako Robotic-Arm Assisted Surgery System [22,23] is a robotic assisted surgery platform designed for precision drug dispensing and product assembly. This system is powered by advanced software that helps ensure accuracy and reduce human error during the manufacturing process.
<i>Syntegon, Germany</i>	Machines are used for tasks like filling, packaging, and labeling of pharmaceutical products.	The RAN series of robotic systems [24,25] are designed for high-speed, precise handling and packaging of various drug formats. These systems are equipped with advanced software and control systems that enable them to adapt to different product types and production requirements.
<i>Yaskawa Motoman, Japan</i>	Robotic systems are employed in the pharmaceutical industry for applications such as drug manufacturing, quality control, and packaging.	The Motoman GP series of robots are known for their precision and reliability in handling delicate pharmaceutical products [26].
<i>Omron Corporation, Japan</i>	Robots are used in applications like drug manufacturing, assembly, and inspection.	Omron's LD Mobile Robot series [27] is designed for material transportation and handling in pharmaceutical manufacturing facilities.
<i>Stäubli Robotics, Switzerland</i>	Robots are utilized for tasks such as drug manufacturing, packaging, and quality control.	Stäubli's TX2 series of robots [28] are known for their cleanroom compatibility, making them suitable for use in sterile pharmaceutical production environments. Their advanced software and control systems ensure precise and efficient operation in various tasks, such as drug manufacturing, packaging, and quality control.
<i>Denso Robotics, Japan</i>	Robots are employed in the pharmaceutical industry for applications like drug manufacturing, packaging, and inspection.	Denso's VS series of robots [29] are designed for high-speed and precision handling of pharmaceutical products, helping to improve productivity and quality.
<i>Honeywell, USA</i>	Offers automated solutions for the pharmaceutical industry, including production management, process monitoring, and quality control systems.	Automated storage and retrieval system (AS/RS), autonomous mobile robots (AMRs), and Pallet Accuglide™ conveyor [30].
<i>IMA Group, Italy</i>	Automated solutions for packaging, dosing, labeling, and other manufacturing processes.	IMA Swiftpack SWIFTLIFT Tablet Elevator and continuous direct compression line [31].

Innovative robotic technologies and automated systems are increasingly being used in the pharmaceutical industry to ensure quality control and maintain high standards for drug production. By automating quality control processes, these technologies can help

reduce the risk of human error, streamline workflows, and improve overall product quality (Figure 3).

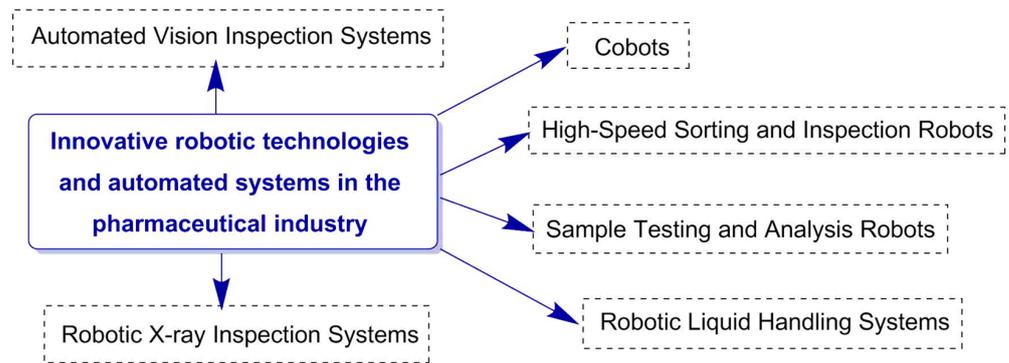


Figure 3. Main directions of application of innovative robotic technologies and automated systems in pharmaceutical manufacturing.

A few examples of innovative robotic technologies and automated systems being used in the pharmaceutical industry to ensure the highest quality standards for drug production are presented in Table 2.

Table 2. Innovative robotic technologies in pharmaceutical production.

Robotic Technologies and Automated Systems	Application
<i>Automated Vision Inspection Systems</i>	Such systems use advanced cameras, sensors, and image processing software to inspect pharmaceutical products, such as tablets [32], capsules [33], and vials [34], for defects or inconsistencies. By automating the inspection process, these systems can quickly and accurately identify issues, such as incorrect labeling, damaged packaging, or improper tablet shapes and sizes, ensuring only high-quality products reach consumers [35].
<i>Collaborative Robots (Cobots)</i>	Cobots [36,37], such as Universal Robots’ UR series, are designed to work alongside human operators in quality control processes. They can be easily programmed and adapted for tasks, such as drug packaging inspection, label verification, and quality control checks. Their advanced safety features ensure minimal risk to human operators while improving the overall efficiency of the quality control process.
<i>High-Speed Sorting and Inspection Robots</i>	Robots like ABB’s FlexPicker and KUKA’s KR AGILUS series are used for high-speed sorting and inspection of pharmaceutical products [37,38]. They can quickly and accurately sort products based on various criteria, such as size, shape, color, or weight, and identify any defects or inconsistencies in the process.
<i>Sample Testing and Analysis Robots</i>	These robotic systems [39] automate the process of collecting and analyzing samples from drug production batches. By using advanced sensors and analytical tools, they can quickly and accurately test samples for quality parameters, such as purity, potency, and stability, ensuring that products meet strict regulatory standards.
<i>Robotic Liquid Handling Systems</i>	These systems [40] are involved in the processes of transferring, measuring, and mixing liquids in the pharmaceutical manufacturing and quality control process. With high precision and accuracy, these robots ensure consistency in drug formulation and reduce the risk of human error, helping to maintain strict quality standards.
<i>Robotic X-ray Inspection Systems</i>	These systems [39] use advanced X-ray technology to inspect pharmaceutical products and packaging for defects, such as foreign particles, contaminants, or improper sealing. By automating this process, these robots can quickly and accurately identify issues, ensuring that only high-quality products reach the market.

The use of 3D printing, also known as additive manufacturing, in the field of drug production, has been gaining traction in recent years [41–43]. This innovative technology allows for the layer-by-layer creation of objects from a digital design using various materials, such as polymers, metals, and ceramics.

In the pharmaceutical industry, 3D printing offers several advantages and potential applications (Figure 4), as outlined below:

- *Personalized medicine* [44]: One of the most promising applications of 3D printing in drug production is the creation of personalized medications. With 3D printing, it is possible to tailor drugs to specific patients by adjusting the dosage, release profile, and even the combination of active pharmaceutical ingredients (APIs) based on individual needs. This can lead to more effective treatments and reduced side effects for patients.
- *Complex drug formulations* [45]: Three-dimensional printing enables the production of complex drug formulations that may be challenging for manufacture using traditional methods. For example, it can create multilayered tablets with different release profiles for each layer or intricate geometries that can affect the drug’s dissolution and absorption rates.
- *Rapid prototyping and development* [46]: Three-dimensional printing can significantly speed up the drug development process by allowing researchers to create and test new drug formulations and delivery systems. This can reduce the time and cost associated with bringing new medications to market.
- *On-demand production* [47,48]: Three-dimensional printing enables decentralized and on-demand drug production, allowing for smaller batch sizes and reduced inventory costs. This can be particularly beneficial where immediate access to medication is needed, such as in disaster relief or remote locations.
- *Reducing waste* [49–51]: Three-dimensional printing allows for more precise material usage, which can help reduce waste in the drug manufacturing process. This can lead to cost savings and a reduced environmental impact.

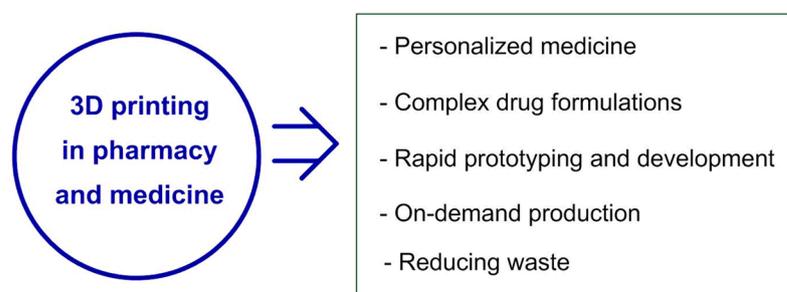


Figure 4. Application of 3D printing in pharmacy and medicine.

Several companies and research institutions are actively exploring the potential of 3D printing in drug production (Table 3).

Table 3. Directions of applications of 3D printing in pharmacy and medicine.

Company/Research Institution, Country	Application of 3D Printing	3D-Printed Pharmaceutical Product/Patented Technology
<p><i>Aprecia Pharmaceuticals, USA</i></p>	<p>Aprecia is a pioneer in 3D printing for pharmaceuticals and developed the first FDA-approved 3D-printed drug, Spritam. The company’s proprietary ZipDose technology enables the creation of rapidly dissolving oral medications, which can improve patient adherence and make it easier for patients to take their medication.</p>	<ul style="list-style-type: none"> - ZipDose technology [52]; - Drug Spritam [53–55].

Table 3. Cont.

Company/Research Institution, Country	Application of 3D Printing	3D-Printed Pharmaceutical Product/Patented Technology
<i>FabRx, UK</i>	FabRx focuses on developing 3D printing technologies for personalized medicine. The company researches various 3D printing methods, such as selective laser sintering (SLS) [56], fused deposition modeling (FDM) [57], and stereolithography (SLA) [58], to produce customized drug dosages and release profiles based on individual patients.	<ul style="list-style-type: none"> - Personalized polypills [59] that contain multiple active pharmaceutical ingredients (APIs) in a single tablet, with each ingredient printed in a separate compartment. The patented technology enables the customization of drug dosage and release profiles based on individual patient needs. - Printlets [60] can be designed with multiple compartments to contain different APIs, which can be released at different rates for a tailored therapeutic effect. The technology employs FDM 3D printing to create solid oral dosage forms [60].
<i>Nano3D Biosciences, USA</i>	Nano3D Biosciences focuses on developing bioprinting technologies for drug discovery and development [61].	Magnetic 3D bioprinting technology [62,63] can be used to create complex tissue structures for drug testing, which can help improve the efficiency and accuracy of drug development processes.
<i>ExOne, USA</i>	ExOne explores the use of its technology to create custom drug dosages and formulations, as well as drug delivery devices [64–66].	Freeman technology [65].
<i>T3D Therapeutics, USA</i>	T3D Therapeutics focuses on using 3D printing technology to create customized medications for the treatment of neurological disorders, such as Alzheimer’s disease.	Their 3D printing technology enables the precise control of drug release profiles, potentially improving treatment outcomes and reducing side effects for patients [67].
<i>Paragon Medical, USA</i>	Paragon Medical focused on the development of 3D printing technologies for various industries, including pharmaceuticals [68].	The company researches and develops new techniques for creating complex drug formulations, drug delivery devices, and personalized medications using 3D printing [69].
<i>Exaddon, North Carolina State University and the University of North Carolina, USA</i>	Exaddon develops microneedles made from copper that can be designed with varying shapes and sizes to control the release of drugs through the skin for delivery.	Exaddon technology for the printing of microneedles [70,71].

Microneedles are made from biodegradable polymers and can be designed with varying shapes and sizes to control the release of drugs through the skin. This technology has potential applications in painless, targeted drug delivery and vaccinations [70,71].

While 3D printing holds great promise for the future of drug production, there are still challenges to be addressed, such as regulatory issues, quality control, and the scalability of the technology. As research continues and technology matures, 3D printing will likely play an increasingly significant role in the pharmaceutical industry.

3. Robotic Drug Delivery Systems

Innovative robotic drug delivery systems are being developed to improve the efficiency, safety, and patient experience in drug administration. These systems often incorporate advanced technologies such as artificial intelligence, machine learning, and automation to optimize treatment outcomes. The development of innovative robotic drug delivery systems (Figure 5) promises to revolutionize the way medications are administered to patients, offering more precise and personalized treatments [72–75]. In this section, we consider examples (Table 4) of robot-assisted drug delivery, implantable drug delivery devices, nanorobots for drug delivery, etc.

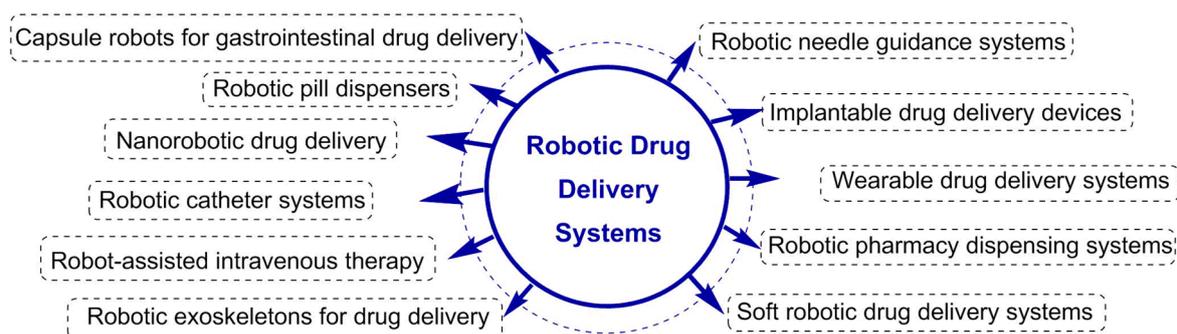


Figure 5. Applications of innovative robotic drug delivery systems in medicine.

Table 4. Examples of innovative robotic drug delivery systems.

Drug Delivery System	Application	Example of Drug Delivery Systems
<i>Robot-assisted intravenous (IV) therapy</i>	These systems for intravenous medications [76] help minimize human errors, improve safety, and reduce the risk of contamination during the preparation process.	RIVA (Robotic IV Automation) system from ARxIUM or the IV Compounding Robot from Aesynt
<i>Capsule robots for gastrointestinal drug delivery</i>	Capsule robots can provide external control to deliver drugs to specific locations within the gastrointestinal tract. These robots have the potential to improve drug absorption, reduce side effects, and enable targeted therapy for conditions such as inflammatory bowel disease or gastrointestinal tumors [74,77].	RoboCap from Massachusetts Institute of Technology
<i>Robotic needle guidance systems</i>	Such systems can accurately position needles for drug injections or biopsies. These systems use advanced imaging and AI algorithms to improve accuracy, reduce complications, and shorten procedure times [78–80].	Robotic needle guidance systems from XACT Robotics
<i>Implantable drug delivery devices</i>	Such devices can be remotely controlled to release drugs on demand or according to a predetermined schedule. Such devices have the potential to improve patient adherence, reduce the frequency of drug administration, and enable more precise dosing [81].	LACRISERT from Bausch + Lomb

Table 4. Cont.

Drug Delivery System	Application	Example of Drug Delivery Systems
<i>Wearable drug delivery systems</i>	Systems can automatically administer drugs according to programmed schedules or in response to real-time physiological data. These devices can improve treatment outcomes by ensuring consistent drug delivery and reducing the burden on patients [82,83].	Chrono Therapeutics' SmartStop and the insulin delivery systems developed by Insulet and Tandem Diabetes Care
<i>Robotic pharmacy dispensing systems</i>	Automated pharmacy dispensing systems [84–86] help to improve the accuracy and efficiency of medication dispensing, reducing the risk of medication errors and freeing up pharmacy staff to focus on patient care.	The PillPick system from Swisslog Healthcare or the ARxIUM FastPak Elite
<i>Soft robotic drug delivery systems</i>	These systems can change shape and size to navigate through the body and deliver drugs to specific locations [87]. These flexible robots made from materials like hydrogels or elastomers can adapt to the body's internal environment and minimize the risk of injury during drug delivery.	Millirobot from City University of Hong Kong and Shenzhen Institutes of Advanced Technology
<i>Nanorobotic drug delivery</i>	These systems use nanoscale robots to transport and release drugs within the body. These tiny robots can be engineered to respond to specific environmental stimuli, such as pH or temperature, ensuring targeted and controlled drug delivery [88,89].	Nanobots for cancer treatment from Elan Pharmaceuticals, Merck's Emend, and Wyeth's Rapamune
<i>Robotic exoskeletons for drug delivery</i>	Robotic exoskeletons are being researched for drug delivery applications [90,91]. These wearable robotic devices could potentially administer medications directly into the bloodstream, bypassing the gastrointestinal system and improving bioavailability.	Robotic exoskeletons from ReWalk Robotics and Ekso Bionics
<i>Robotic catheter systems</i>	Robotic catheter systems enable precise navigation of catheters within the body to deliver drugs directly to targeted tissues or organs [92–94]. This can enhance the effectiveness of treatments while reducing systemic side effects.	Robotic catheter systems from Auris Health and Corindus Vascular Robotics
<i>Robotic pill dispensers</i>	Robotic pill dispensers use automation and artificial intelligence to dispense the right medications at the right time for patients [86,87]. These systems help improve patient adherence to treatment regimens and reduce the risk of medication errors [95,96].	The Pillo Health or the Hero Medication Dispenser

These examples of innovative robotic drug delivery systems have the potential to transform medication administration, making it safer, more precise, and less burdensome for patients and healthcare professionals. As technology advances, we believe new and improved robotic drug delivery systems will continue to emerge.

4. Robotic Technologies in Medicine

In addition to applications in pharmacy, robotic technologies are also transforming medical practice, facilitating more accurate diagnoses and minimally invasive treatments. They are transforming various aspects of medicine (Figure 6), including diagnostics, surgery, rehabilitation, and drug delivery [97–99].

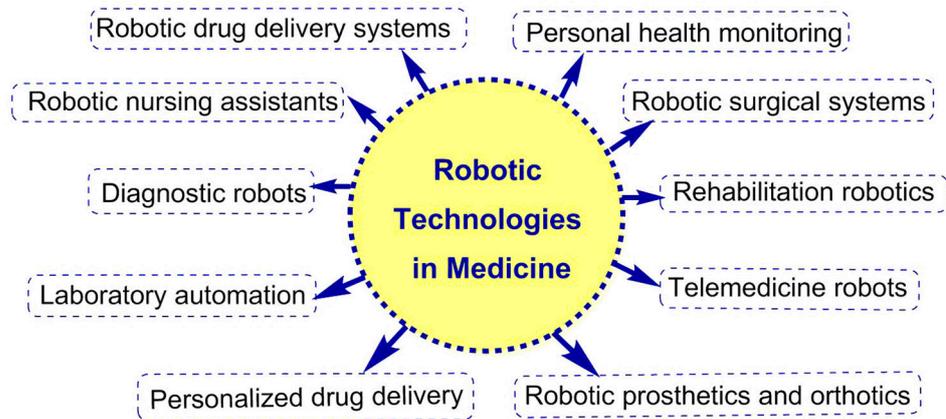


Figure 6. Application of robotic technologies in medicine.

The integration of robotics in medicine is aimed at improving precision, reducing human error, and enhancing patient outcomes. Robotic technologies in personal medicine are aimed at enhancing patient care, increasing accessibility, and tailoring treatments to individual needs (Table 5).

Table 5. Robotic technologies applied in medicine.

Direction of Robotic Technology Applications	Application
<i>Personal health monitoring</i>	Wearable robotic devices, such as smartwatches or fitness trackers, monitor an individual’s vital signs, sleep patterns, and activity levels. This information can be used to provide personalized health insights and recommendations [100].
<i>Robotic surgery</i>	Robotic surgical systems, such as the da Vinci Surgical System [101] by Intuitive Surgical, are used to perform minimally invasive procedures with greater precision and control. These systems provide enhanced visualization, improved dexterity, and increased accuracy, leading to shorter recovery times and reduced risk of complications for patients.
<i>Rehabilitation robotics</i>	Robotic devices are being used to support physical therapy and rehabilitation. Examples include exoskeletons like the ReWalk system [102], which assists individuals with spinal cord injuries in walking, and robotic devices like the InMotion Arm by Bionik Laboratories [103]. The latter helps patients regain upper limb function and can be used at home to support physical therapy and rehabilitation for patients recovering from stroke or other neurological conditions. These devices provide personalized therapy, enabling patients to receive tailored treatment in the comfort of their own homes.
<i>Telemedicine robots</i>	Telepresence robots [104–106], such as those developed by InTouch Health and Intuitive Surgical, enable healthcare professionals to remotely diagnose, consult, and treat patients. These robots use high-definition cameras and real-time communication systems to connect patients with healthcare providers, regardless of their physical location.

Table 5. Cont.

Direction of Robotic Technology Applications	Application
<i>Robotic prosthetics and orthotics</i>	Advanced prosthetic limbs, such as the DEKA Arm (also known as the “Luke Arm”) [107] and the BiOM T2 Ankle [108], use robotic technology to mimic natural limb movements and provide users with increased functionality and mobility [109].
<i>Robotic drug delivery systems</i>	Innovative robotic drug delivery systems are being developed to improve the efficiency, safety, and patient experience in drug administration (see item 3).
<i>Robotic nursing assistants</i>	Robotic nursing assistants, such as Moxi by Diligent Robotics [110] and Robear by RIKEN [111], are designed to perform routine tasks like delivering medication, collecting lab samples, and assisting with patient transport. These robots help free up medical staff to focus on more complex patient care tasks.
<i>Diagnostic robots</i>	Robotic systems are being developed to aid in diagnostics. For example, the PillCam by Given Imaging [112] is a swallowable capsule camera that captures images of the gastrointestinal tract. Another example is the robotic catheter system by Auris Health [93], which aids in diagnosing and treating lung cancer.
<i>Laboratory automation</i>	Robotic systems like the Hamilton STAR and Tecan Freedom EVO [113] are used to automate laboratory processes, increasing efficiency, reducing human error, and improving the quality of data collected in medical research.
<i>Personalized drug delivery</i>	Robotic drug delivery systems like those discussed earlier can be tailored to individual patient needs, ensuring targeted and controlled drug delivery for optimal therapeutic outcomes.

These examples demonstrate the significant impact of robotic technologies in medicine. As technology continues to advance, we can expect further integration of robotics in health care, leading to improved patient care and outcomes.

In addition, the classification of robotics applications in pharmacy and medicine is complemented by the use of robots for motion planning, robot mechanism design, kinematics, control, optimization, etc. Motion planning is a critical aspect of robotics and AI applications in health care. It involves determining the sequence of movements that a robot must perform to achieve a specific task [114]. In the context of pharmacy and medicine, motion planning can be used in surgical robots to plan the path of surgical instruments, ensuring they avoid critical structures in reaching the target area [115].

The design of the robot mechanism is crucial for its functionality. In pharmacy, robots are designed to handle tasks such as dispensing pills, searching for medication, and managing stock levels [116]. These robots have the capability to work together with the user or autonomously. They can perform the exact same tasks that a user would in day-to-day activities [117].

Kinematics involves the study of motion without considering the forces that cause it. In health care, kinematic models are used to simulate the movement of surgical robots, allowing for precise control during procedures [118].

Control systems in health care can be used to guide surgical robots during procedures, ensuring they move accurately and safely [115]. In pharmacy, control systems can be used to manage the operation of drug-dispensing robots, ensuring they dispense the correct medication in the correct dosage [117].

In health care, optimization can be used to improve the efficiency and effectiveness of robotic systems. For example, AI can be used to optimize the motion planning of surgical robots, ensuring they take the most efficient path during procedures [119]. In pharmacy, optimization can be used to improve the operation of drug dispensing robots, reducing errors and improving efficiency [120].

5. Artificial Intelligence and Robotics in Drug Discovery and Health Care

Artificial intelligence has been a significant driving force behind the rise of robotic technologies in health care. AI and robotics are transforming health care (Figure 7) by improving diagnostics, treatment, and patient care [121,122].

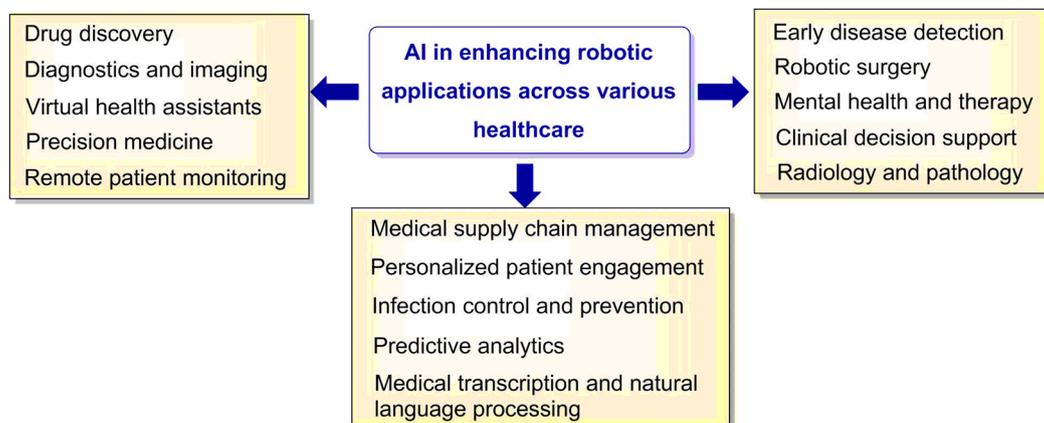


Figure 7. Application of AI in health care.

These advancements are being driven by numerous companies, both established and emerging. In this section, we considered the role of AI in enhancing robotic applications across various healthcare domains and the potential synergies between AI and robotics (Table 6).

Table 6. AI and robotics in drug discovery and health care.

Direction of AI and Robotics Applications	Application	Companies Working on These Solutions
<i>Drug discovery</i>	Analysis of large datasets and identification of potential drug candidates or targets, significantly speeding up the drug discovery process.	Atomwise [123,124], BenevolentAI [125], Insilico Medicine [126]
<i>Diagnostics and imaging</i>	Analysis of medical images, such as X-rays, MRIs, or CT scans and faster speed and accuracy of detection of abnormalities than human specialists.	Aidoc [127,128], Zebra Medical Vision [129], PathAI [130]
<i>Precision medicine</i>	Analysis of genetic, clinical, and lifestyle data to help tailor medical treatments to individual patients, improving outcomes and reducing side effects.	Tempus [131], Deep Genomics [132,133], 23andMe [134]
<i>Virtual health assistants</i>	AI-powered virtual health assistants [135], such as chatbots or voice assistants, to provide medical advice, answer health-related questions, and help schedule appointments.	Ada Health [136], Babylon Health [137], Buoy Health [138]
<i>Remote patient monitoring</i>	Analysis of data collected from wearable devices, alerting healthcare providers of any abnormalities, allowing for early intervention and improved patient care.	Biofourmis [139], Current Health [140]

Table 6. Cont.

Direction of AI and Robotics Applications	Application	Companies Working on These Solutions
<i>Robotic surgery</i>	Robotic surgical systems, such as the da Vinci Surgical System [101], enable surgeons to perform minimally invasive procedures with greater precision and control, leading to better patient outcomes.	Intuitive Surgical [101], Medtronic [141], Stryker [22,23]
<i>Early disease detection</i>	Prediction of the likelihood of diseases based on patient data and identification of early warning signs, facilitating early intervention and treatment [142].	Freenome [143], ClosedLoop.ai [144]
<i>Mental health and therapy</i>	AI-driven chatbots and apps provide personalized support and therapy for individuals dealing with mental health issues, such as anxiety, depression, or post-traumatic stress disorder.	Woebot [145], Wysa [146], Talkspace [147]
<i>Radiology and pathology</i>	AI-based algorithms can help radiologists and pathologists interpret medical images, improving diagnostic accuracy and efficiency [148].	Butterfly Network [149], Enlitic [150], Paige.AI [151]
<i>Medical transcription and natural language processing</i>	Transcription and analysis of spoken or written medical language, streamlining the documentation process and reducing the administrative burden on healthcare professionals [152].	Nuance Communications [153], DeepScribe [154], Google Cloud Healthcare API [155]
<i>Clinical decision support</i>	AI-powered decision support tools help healthcare professionals make better-informed decisions, reducing errors and improving patient care [156,157].	IBM Watson Health [158], Cerner [159], ZS [160]
<i>Medical supply chain management</i>	Optimization of the supply chain, helping to manage inventory and reduce waste [161].	Gauss Surgical [162], Swisslog Healthcare [163], Omnicell [164]
<i>Infection control and prevention</i>	Robots equipped with UV-C light technology can be used to sanitize medical facilities, reducing the risk of hospital-acquired infections.	Xenex [165,166], UVD Robots [167,168], Surfacide [169]
<i>Predictive analytics</i>	AI-powered predictive analytics can be used to anticipate patient needs, optimize hospital resources, and identify high-risk patient populations [170].	Medial EarlySign [171]
<i>Personalized patient engagement</i>	Creation of personalized care plans and interventions based on patient data, improving patient adherence to treatment and overall health outcomes [172].	Lark Health [173], Wellframe [174], GYANT [175]

AI has become an essential tool in drug discovery (Figure 8), enabling researchers to accelerate the drug development process, reduce costs, and improve the success rate of new drug candidates.

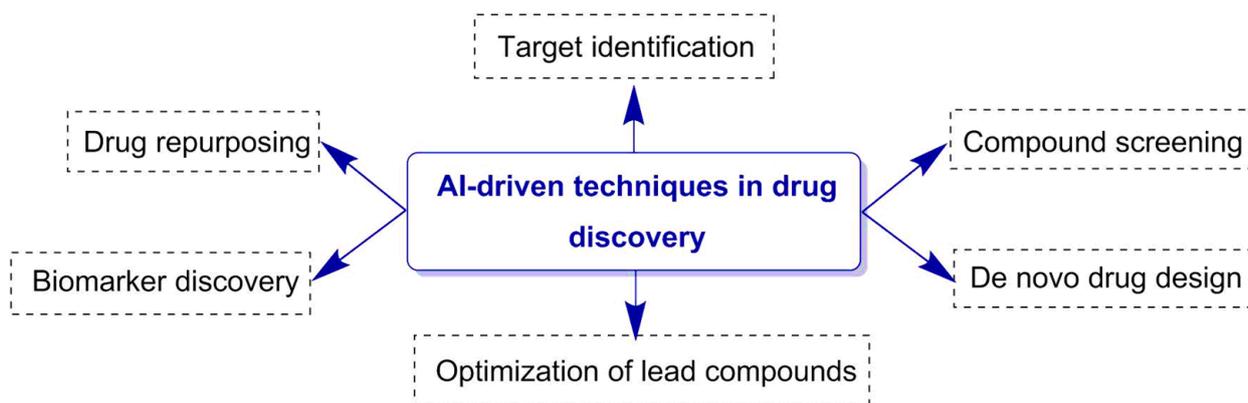


Figure 8. Application of AI-driven techniques in drug discovery.

AI-driven techniques in drug discovery include:

- *Target identification:* AI algorithms can analyze large datasets, such as genomic, proteomic, and metabolomic data, to identify potential drug targets and elucidate disease mechanisms [176]. This process enables researchers to better understand the molecular basis of diseases and pinpoint suitable targets for drug development.
- *Compound screening:* AI-driven virtual screening methods can identify promising drug candidates from vast libraries of compounds more efficiently than traditional high-throughput screening methods. AI algorithms can predict the biological activity, toxicity, and pharmacokinetic properties of potential drug candidates, thereby reducing the time and resources required for experimental validation [177].
- *De novo drug design:* AI can help design new drug molecules from scratch by leveraging deep learning techniques to predict the properties of potential compounds [178]. Generative adversarial networks (GANs) and other machine learning algorithms can create novel molecular structures with the desired biological activity and drug-like properties [179].
- *Drug repurposing:* AI can analyze existing drugs and their effects to identify new therapeutic uses, significantly reducing the time and cost of drug development. By analyzing the molecular profiles of approved drugs, AI can predict their potential efficacy in treating other diseases or conditions [180].
- *Biomarker discovery:* AI can analyze vast amounts of biological data to identify biomarkers that can be used for early disease detection, diagnosis, prognosis, or monitoring treatment response. These biomarkers can help tailor therapies to individual patients, leading to more effective treatments and better patient outcomes [181].
- *Optimization of lead compounds:* AI algorithms can optimize lead compounds by predicting the impact of chemical modifications on their pharmacological properties, such as potency, selectivity, and safety. This approach enables researchers to iteratively improve drug candidates before advancing to preclinical and clinical testing [182].

Numerous companies [123,183–195] are utilizing AI to revolutionize drug discovery, complementing traditional methods and streamlining the development process (Table 7).

AI is revolutionizing drug discovery by enhancing efficiency, decreasing expenses, and facilitating the development of more effective and personalized therapies. As AI technologies continue to advance, their impact on drug discovery and development will only increase [196–198].

Table 7. Companies utilizing AI, machine learning, and big data in drug discovery.

Company Name	Application of AI	Company Homepage
<i>Atomwise</i>	Structure-based drug design and compound screening to identify potential drug candidates	https://www.atomwise.com
<i>BenevolentAI</i>	Identification of drug targets, design of molecules, and optimization of drug candidates	https://www.benevolent.com
<i>Insilico Medicine</i>	Target identification, molecule generation, and drug repurposing	https://insilico.com
<i>Exscientia</i>	Design and optimization of drug candidates in a range of therapeutic areas	https://www.exscientia.ai
<i>Recursion Pharmaceuticals</i>	AI-based image analysis and machine learning to analyze cellular phenotypes for drug discovery and repurposing	https://www.recursion.com
<i>Deep Genomics</i>	Prediction of the effects of genetic mutations and development of therapies for genetic diseases	https://www.deepgenomics.com/platform/
<i>Schrödinger</i>	Computational methods and AI for molecular modeling, design of novel compounds with desired properties, and optimization of existing drug candidates	https://www.schrodinger.com
<i>ARIA Pharmaceuticals</i>	AI-driven drug discovery for various therapeutic areas, leveraging large-scale data integration and machine learning algorithms to identify promising drug candidates	https://ariapharmaceuticals.com
<i>Cyclica</i>	In silico drug discovery using a combination of deep learning and molecular dynamics simulations to predict drug–target interactions, off-target effects, and ADMET properties	https://cyclicarx.com
<i>BioXcel Therapeutics</i>	Identification and development of innovative therapies by repurposing existing drugs and designing new drug candidates	https://www.bioxceltherapeutics.com
<i>Numerate</i>	Design, optimization, and validation of small molecule drug candidates, focusing on areas such as oncology, immunology, and metabolic diseases	http://www.numerate.com
<i>A2A Pharmaceuticals</i>	Design and development of novel drug candidates for difficult-to-drug targets, aiming to treat cancer, infectious diseases, and other conditions	https://www.a2apharma.com
<i>Cloud Pharmaceuticals</i>	Design and optimization of drug candidates, focusing on areas such as oncology, inflammation, and central nervous system disorders	https://www.cloudpharmaceuticals.com
<i>Lantern Pharma</i>	Identification and development of precision oncology therapies by repurposing existing drugs and discovering new drug candidates	https://www.lanternpharma.com
<i>Owkin</i>	Analysis of multimodal medical data, including imaging and omics data, to identify biomarkers and develop predictive models for drug discovery and personalized medicine	https://owkin.com

6. Ethical Considerations and Challenges in Implementing AI and Robotic Technologies in Health Care

As robotic technologies continue to advance and become more integrated into health care [199], several ethical considerations and challenges arise. These concerns are crucial to address to ensure the responsible and equitable deployment of these technologies in medical settings (Figure 9).

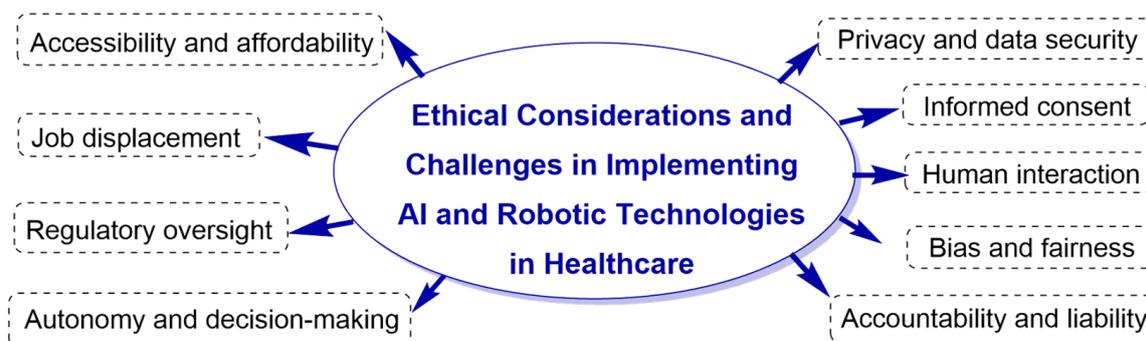


Figure 9. Directions of ethical considerations and challenges in implementing AI and robotic systems in health care.

Robotic systems and AI often require access to large amounts of sensitive patient data, raising concerns about *privacy and data security*. Ensuring that patient information is protected and only used for intended purposes is critical.

Main solutions to ensure data security in health care include educating healthcare staff about security, restricting access based on roles, implementing data usage controls, monitoring data usage, encrypting data at rest and in transit, securing mobile devices, addressing risks from connected devices, conducting regular risk assessments, maintaining encrypted offline backups, and staying vigilant about software vulnerabilities through patches and updates [200–205].

Cyber threats such as data breaches, cyber attacks, and database hacking pose significant challenges to healthcare systems. However, there are several strategies that can be employed to improve the resilience of digital health solutions against these threats: strengthening cybersecurity resilience [206], improving cybersecurity posture [207], and cyber risk management [208].

Healthcare organizations can strengthen their cybersecurity resilience by developing an ever-maturing security posture that helps maintain resilience to new threats [206]. This involves simulating cybersecurity threats and resulting operational impacts regularly, which can help organizations get better at identifying, managing, and eventually eliminating entire categories of threats [206]. Healthcare organizations are encouraged to strengthen their cyber posture. This involves understanding where all electronically protected health information (ePHI) exists across the organization—from software to connected devices, legacy systems, and elsewhere across the network [207]. Some best practices include maintaining offline, encrypted backups of data and regularly testing backups; conducting regular scans to identify and address vulnerabilities, especially those on internet-facing devices, to limit the attack surface; and regular patches and updates of software and operating systems [207].

Accountability and liability in implementing robotic technologies in healthcare are complex issues. The use of opaque AI-powered systems in clinical decision making raises concerns about accountability and the allocation of responsibility and legal liability [209]. A review [209] found that there are multiple concerns about opacity, accountability, responsibility, and liability when considering the stakeholders of technologists and clinicians in the creation and use of AI systems in clinical decision making.

The gradual embrace of AI in medicine also raises a critical liability question for the medical profession. Who should be responsible when these devices fail? Taking the example of a surgeon using robotically assisted surgical devices with safety features, the next question arises [210]. Would the injured patient be able to hold the device manufacturer legally responsible for the sensor's failure, or would only the physician using the device be responsible? This scenario highlights the complexities surrounding liability in the event of an AI-driven medical device failure [210].

The WHO emphasizes that the potential of AI in healthcare can be realized only if ethical considerations and human rights are central to its development, deployment, and use [211]. In a report based on two years of expert consultations, the WHO underscores that while AI offers benefits like improved diagnosis and patient empowerment, its misuse and harm must be avoided. The document outlines six guiding principles for effective AI regulation and governance in health care: safeguarding human autonomy, promoting safety and well-being, ensuring transparency and explainability, fostering responsibility and accountability, guaranteeing inclusiveness and equity, and encouraging responsive and sustainable AI systems [211].

Informed consent is a crucial aspect of implementing robotic technologies in health care. Informed consent in the context of applying artificial intelligence in medical diagnostic consultations is a complex issue. The main ethical and legal concerns arise from the new health phenomena powered by intelligent machines [212]. There are several ethical and legal challenges when it comes to informed consent. These include the right to explanation, privacy, and informed consent when applying artificial intelligence in medical diagnostic consultations [212]. Digital technologies have been used to apply and test innovative formats of informed consent [213]. These tools have not been found to negatively affect any of the outcomes, and overall, multimedia tools seem desirable [213]. Multimedia tools have been indicated to have a higher impact than videos only [213]. Understanding, satisfaction, and participation were investigated for digital tools versus the non-digital informed consent process [213].

The increased use of robots and AI in health care may reduce the *human interaction* that is often an essential aspect of care, potentially impacting the patient-provider relationship. In a study performed in the emergency department at Brigham and Women's Hospital [214], researchers found that a large majority of patients reported that interacting with a healthcare provider via a video screen mounted on a robot was similar to an in-person interaction with a healthcare worker. This suggests that while patients are open to the use of AI and robotics in their care, the technology should be designed and used in a way that complements rather than replaces the human touch [214]. There are some ways to strike a balance: patient-centered design, human oversight, communication, training for healthcare providers, and ethical guidelines [215,216].

Bias and fairness are critical issues in the implementation of AI and robotic systems in health care. Bias in AI systems can come from various sources, such as data, algorithmic, and human decision biases [217]. For instance, if the data used to train an AI system are not representative of the population it serves, the system may inadvertently perpetuate existing biases [217]. Biased AI systems can lead to unfair outcomes and perpetuate existing inequalities. This can be particularly harmful in health care, where decisions can have significant impacts on patients' health and well-being [217]. There are several strategies to mitigate bias in AI systems. These include data preprocessing, model selection, and postprocessing. Tackling bias in AI demands a comprehensive strategy that encompasses diverse and representative datasets, increased transparency, and accountability. It requires the exploration of alternative AI models prioritizing ethical considerations and fairness [217]. Ensuring fairness and mitigating bias in AI systems require interdisciplinary collaboration. This includes collaboration between technologists, clinicians, ethicists, and legal experts, among others [217]. Fairness should be conceived of as an ethical value [218]. Fairness requires more than non-discrimination and the absence of biases, as well as more than just

distribution; it needs to ensure that healthcare machine learning algorithms respect persons both as persons and as particular individuals [218].

The adoption of robotic technologies in health care has the potential to lead to *job displacement* for some healthcare professionals. However, it is important to note that these technologies are also creating new roles and opportunities within the healthcare sector [216]. There are some strategies to prepare the workforce for this change: retraining and skill development, education and awareness, career counseling and support [213], and policy measures involving things like unemployment insurance, job placement services, and other forms of support [219].

Accessibility and affordability are crucial considerations when implementing robotic technologies in health care. Automation technologies such as process automation bots, machine learning algorithms, and physical robots have the potential to reshape work for everyone [220]. If automation's full potential were achieved, it could have a significant impact in terms of reducing costs and improving the affordability of health care [220].

Using robots in health care has advantages, particularly in reducing contact with healthcare providers during the COVID-19 pandemic via a video screen mounted on a robot [214].

To ensure robotic technologies in health care are made available to a broad range of patients and healthcare providers, efforts must be made to reduce costs [220], improve acceptance [211], and address implementation challenges [221].

Robotic technologies in health care require appropriate *regulatory oversight* to ensure their safety, efficacy, and ethical use. This oversight must be adaptive and able to accommodate the rapid pace of technological advancements. A white paper by UL presents the essential regulatory considerations that apply to medical devices, including robotic devices intended for use in medical applications [222]. It discusses the key drivers in the growth of medical robotics; outlines the various types of medical robotic devices that are potentially subject to regulatory review; and details safety, quality, and other requirements and considerations applicable to medical robotic technologies [222]. The use of robotics and AI in health care poses problems of regulatory complexity [223]. Current socio-economic challenges affecting health care in Europe may justify the use of AI and robotics [223].

Autonomy and decision making in robotic technologies in health care pose significant challenges. As AI-driven robots become more autonomous, it is essential to establish guidelines with respect to the extent to which they can make decisions without human input, particularly in critical healthcare scenarios.

Healthcare decisions often involve complex considerations and a deep understanding of the patient's condition, preferences, and context. It can be challenging for AI-driven robots to replicate this nuanced decision-making process [216]. AI algorithms, particularly those based on machine learning, can be "black boxes" that make decisions based on patterns in data that are not easily understandable by humans [216]. This lack of transparency can make it difficult for healthcare providers and patients to trust the decisions made by these systems [213]. One potential solution is to ensure that there is always human oversight of the decisions made by AI-driven robots [224]. This allows healthcare providers to step in if they disagree with a decision or if the system fails [224]. Efforts are being made to develop AI systems that can explain their decisions in a way that humans can understand [224]. Ethical guidelines and regulations can help ensure that AI-driven robots are used in a way that respects patient autonomy and other ethical principles. These guidelines should be developed with input from a wide range of stakeholders, including healthcare providers, patients, ethicists, and AI experts [224].

Addressing these ethical considerations and challenges requires collaboration among healthcare providers, technology developers, regulators, and policymakers. This collaboration will help ensure that robotic technologies are integrated responsibly and ethically into health care, ultimately improving patient outcomes and the overall quality of care.

7. Future Promising Technologies and Research Opportunities for Robotics Technologies and AI in Pharmacy and Medicine

The evolution of robotic technologies and AI in pharmacy and medicine promises an exciting future of unprecedented advances and transformative change.

Healthcare industry leaders are demonstrating a growing commitment to AI, as 37% have outlined plans to prioritize investments in AI within the next three years [225]. The global COVID-19 pandemic has expedited the transition to remote care, with 42% of healthcare leaders intending to sustain this trend [225]. Moreover, significant advancements in AI exemplified by breakthroughs like AlphaFold and RoseTTAFold are poised to revolutionize drug discovery by potentially multiplying the opportunities to identify new drugs manifold [5]. These trends collectively signal a transformative phase in health care that underscores the pivotal role of AI in shaping the future of patient care, medical research, and healthcare operations.

Future directions in health care underscore a commitment to building resilience and readiness for the challenges ahead. Healthcare leaders are strategically investing in digital health technologies that enable adaptability in the face of changing circumstances. The trend towards remote care will continue as healthcare leaders allocate resources to technologies that facilitate remote consultations and virtual healthcare services [225]. In drug discovery, researchers are turning to AI and supercomputing as powerful tools. By building generative AI models of chemical structures, the drug discovery process will be accelerated, potentially changing the landscape of pharmaceutical research and development [5]. Therefore, these future directions reflect a proactive approach to innovation, adaptability, and transformative change within the healthcare industry.

AI stands out as a transformative force among promising technologies, poised to enhance healthcare delivery globally. Its potential spans from improving diagnostic accuracy and clinical care to boosting health research, drug development, and public health interventions [211]. Complementing AI's capabilities, supercomputing emerges as a powerful tool, especially for complex scientific and data-intensive tasks like drug discovery. The robust computational abilities of supercomputers hold potential to revolutionize the drug design process [5]. Additionally, RPA introduces automation to the healthcare sector, particularly in pharmacy settings. Through software robots, RPA streamlines tasks such as prescription filling, inventory management, and insurance claim processing, optimizing efficiency and resource allocation [226].

Promising research opportunities are on the horizon, driving the convergence of cutting-edge technologies and healthcare solutions. For example, NVIDIA launched Cambridge-1, the UK's most powerful supercomputer, to help British healthcare researchers solve some of the industry's most urgent healthcare challenges [5]. NVIDIA is collaborating with AstraZeneca to build a transformer-based generative AI model for chemical structures [5] that will allow researchers to leverage massive datasets using self-supervised training methods and enable faster drug discovery [5]. Another promising research area is the patient experience with robots [214].

However, for these digital health solutions to be sustainable, they must be financially viable, scalable, and capable of facilitating broad user adoption in the long term. The financial viability of AI and robotic technologies in health care is a critical factor for their adoption and long-term sustainability [216]. The development and deployment of these technologies requires significant investment [211]. Scalability is another key factor in the sustainability of these technologies. The healthcare sector stands to gain meaningfully from automation technologies [211]. To capture this opportunity, companies need to be more thoughtful and organized in terms of orchestrating and scaling automation programs [220]. Moreover, systems trained primarily on data collected from individuals in high-income countries may not perform well for individuals in low- and middle-income settings [211]. Therefore, it is essential to develop scalable solutions that cater to a broader demographics. The ability to facilitate broad user adoption is crucial for the long-term sustainability of these digital health solutions. User adoption can be influenced by several factors,

including the perceived usefulness and ease of use of the technology, as well as trust in the technology [214,225]. Finally, a human-centered design that puts healthcare providers and patients first is needed for AI and robotic technologies to be successful in health care [226,227]. This involves an understanding of users' needs and experiences, as well as the design of solutions that are easy to use and add value to the lives of users [227].

8. Conclusions

The future of robotic technologies and AI in health care appears promising and transformative. As these technologies continue to evolve, they hold the potential to revolutionize various aspects of health care, ranging from drug discovery and manufacturing to diagnostics, treatment, and patient care. They are transforming the landscape of pharmacy and medicine, offering significant improvements in pharmaceutical manufacturing, drug delivery, medical procedures, diagnostics, and disease management.

The integration of robotics and AI into healthcare systems can lead to increased efficiency, improved patient outcomes, and reduced costs. Furthermore, these advancements can help address some of the most pressing challenges in health care, such as the growing demand for personalized medicine, the need for more effective and targeted therapies, and the mitigation of human error in clinical settings.

Nevertheless, the widespread adoption of these technologies also raises ethical considerations and challenges, including with respect to privacy and data security, accountability and liability, informed consent, human interaction, bias and fairness, job displacement, accessibility, affordability, regulatory oversight, and autonomy in decision making. To ensure the responsible and equitable implementation of robotic technologies in health care, collaboration among stakeholders is essential.

As we move forward, it is crucial to balance embracing the benefits of these technologies with preservation of the human touch, which is fundamental to health care. Continuous investment in research and development will be essential in shaping a future where innovative robotic technologies are seamlessly integrated into pharmacy and medicine. Creating appropriate regulatory frameworks and ethical guidelines will also play an important role in ensuring benefits for patients and healthcare providers.

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