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Leveraging Robotics in the Digital Transformation of Healthcare for Global Pandemic Response

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ABSTRACT

This paper explores the dynamic integration of robotics into healthcare and related fields, particularly in response to the challenges posed by the COVID-19 pandemic. Robotics have emerged as crucial tools in reducing direct human contact, thereby enhancing cleaning, sterilization, and overall support across hospitals and quarantine facilities. This technological adoption significantly protects healthcare workers and doctors who are at the forefront of managing the COVID-19 crisis, minimizing their risk of exposure. The core aim of this research is to underscore the vital role of medical robotics not just in routine healthcare, but as a strategic asset during the pandemic. By illustrating the connection between robotic technology and COVID-19 management, the paper encourages hospital administrations to fully leverage these innovations in various medical procedures. This is particularly relevant given the rise of telemedicine, which similarly helps reduce physical interactions in medical settings. Moreover, the remarkable success seen in the health sectors of countries like South Korea and China in containing the pandemic underscores the indispensable role of advanced medical technology. The effective use of robotics has been a key component of their strategy to gain a proactive handle on the spread of the virus.

Keywords: Medical robots; COVID-19; healthcare digitization; pandemic; Robotic

I. INTRODUCTION

On January 30, 2020, the World Health Organization (WHO) officially designated the COVID-19 outbreak as a global emergency, citing its swift spread across the globe. The emergence of the virus, first detected in Wuhan City, China in December 2019, swiftly escalated into a pandemic, reaching nearly every country, excluding Antarctica. This rapid spread had a profound impact on global economies, triggering stock market crashes in multiple nations. Despite limited access to comprehensive public data, researchers worldwide have tirelessly worked to understand the magnitude and dynamics of the pandemic. They have tracked the rate of progression and various patterns of transmission. Recent clinical findings reveal that many COVID-19 patients experience minimal symptoms during the initial four days, underscoring the virus's ability to transmit stealthily and efficiently. Experts have noted that COVID-19 is significantly more infectious and deadlier than the common flu, highlighting the serious threat it poses to global health.

Figure 1. Total worldwide deaths due to COVID-19 per million people (as on May 27, 2020) [4].

As of May 26, 2020, the World Health Organization (WHO) reported in their situational report number 127 that globally, there have been 5,404,512 confirmed cases of COVID-19, resulting in 343,514 deaths [5]. The data suggests that older individuals face a significantly higher risk of death from the virus than younger people, and within the same age bracket, men are more vulnerable than women. Individuals with pre-existing health conditions such as cardiovascular diseases, hypertension, diabetes, cancer, and chronic respiratory diseases are at a heightened risk of severe complications and mortality from COVID-19 [4]. The countries that have been most impacted include the United States, China, Italy, Iran, Brazil, France, the United Kingdom, and

Germany, as indicated in Figure 2. COVID-19 spreads in several ways, including through pre-symptomatic, symptomatic, and asymptomatic transmission, highlighting the virus's highly contagious nature. To mitigate the spread of the virus, public health measures such as the use of hand sanitizers, wearing face masks, and maintaining social distancing are crucial. These practices help prevent transmission through sneezing, touching, and handshaking. In the medical and healthcare sectors, the use of personal protective equipment (PPE), including N-95 masks and gloves, is essential for the safe management of COVID-19 cases. The importance of PPE underscores the need for stringent protocols to protect healthcare workers from exposure. Additionally, innovative solutions like medical robots and telemedicine are gaining attention as effective ways to manage and control the spread of the virus among larger populations [6]. These technologies not only reduce the risk of infection but also support ongoing social distancing efforts in healthcare settings.

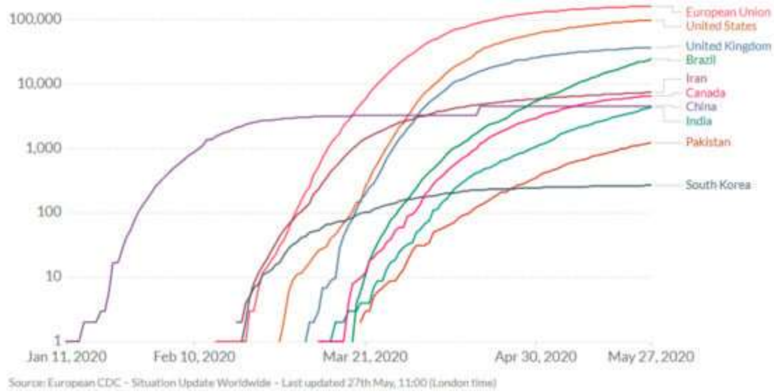

Figure 2. Total confirmed deaths due to COVID-19 on log scale (as on 27 May 2020) [**4**].

In light of the overwhelming challenges presented by the COVID-19 pandemic, robots have emerged as vital assets in supporting the health and well-being of patients. These technological aides not only supplement the efforts of medical personnel in hospitals overwhelmed by patient loads but in some cases, may also take over certain tasks completely. Today, robotic systems have become integral to medical support across various healthcare facilities[7]. Particularly in China, robots are deployed for several critical tasks including cleaning and preparing meals in areas that pose high risks of infection to human workers. This research paper underscores the pivotal role that robotics can play in managing healthcare needs during the COVID-19 crisis and potentially in future pandemics. The aim of this study is to delve into the potential of strategic healthcare innovations through the adoption of robotics, with a focus on managing the global COVID-19 crisis. The findings of this study are intended to offer strategic insights to decision-makers and policymakers, enhancing healthcare quality in the face of local and global disasters, pandemics, and similar emergencies. The structure of this paper is methodically organized into several sections: Section 2 outlines the essential requirements of robots within the healthcare sector. Section 3 provides a detailed classification of robotic applications in medicine and related areas. The discussion in Section 4 explores the specific implications of integrating robotics for managing COVID-19. The paper concludes with a summary of key points in Section 5.

II. THE GROWING ROLE OF ROBOTICS IN HEALTHCARE

The deployment of robotics and automation technologies in healthcare continues to expand significantly, as highlighted by numerous studies [8,9]. The International Federation of Robots (IFR) forecasts a sustained growth in the demand for medical robots, projecting that the market could reach a substantial value of 9.1 billion USD by 2022, as depicted in Figure 3. Robots are increasingly being utilized not just to assist physicians and medical personnel in performing intricate and precise procedures, but also to reduce their workload. This contribution from robots enhances the overall efficiency and effectiveness of healthcare services [10].

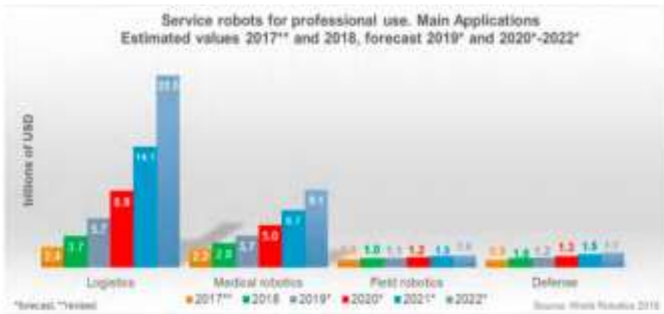

Figure 3. Illustrates the growing global demand for medical robots, as referenced in [11].

2.1 Kinematics and Dynamics in Medical Robotics

The design of kinematics and dynamics for medical robots is tailored to their specific applications. Both serial and parallel configurations are employed in a variety of tasks that range from surgery and rehabilitation to general services within healthcare settings. An example of a parallel kinematic manipulator is the FlexPicker, also known as the "Delta" robot, developed by ABB in Zurich, Switzerland. Originally crafted for surgical use, it has found extensive application in the food manufacturing sector as well. In contrast, most service robots utilized in hospitals are typically mobile robots characterized by their high payload capacities yet limited in their degrees of freedom. Surgical robots, however, boast multiple degrees of freedom, offering flexibility, precision, and reliability. Their performance is comparable to that of highly skilled surgeons, with error margins often less than a few millimeters.

2.2 Control and Dexterity

Effective control systems in medical robotics are vital for achieving high precision, reliability, and repeatability in operations, while also minimizing the impact of external disturbances. The challenge in designing these systems includes ensuring an ample range of motion for the robot's end-effector, allowing it to move precisely along desired paths. Medical robots incorporate advanced technology to fulfill various functions such as cleaning, sterilization, transport, nursing, rehabilitation, and surgery. To manage these complex and agile tasks, robust adaptive controllers are commonly used for navigation and control.

2.3 Sterilization Standards

In the realm of healthcare, robots must adhere to rigorous sterilization protocols to prevent the transmission of infectious diseases. Surgical robots, particularly, use end effectors designed for single use to maintain sterility. Regular sterilization is mandatory for service robots to prevent them from becoming vectors for disease. Additionally, robots used in food preparation have their specific cleaning protocols, ensuring they are safe to use after each session.

2.4 Ensuring Operator Safety

Safety is paramount when it comes to medical robotics. It is crucial that robots operating within hospital environments do not pose any threat to the medical staff, operators, or patients. Surgical robots, for instance, must comply with international safety standards such as IEC 80601-2-77 to ensure they can be safely used during operations. Rehabilitation robots also adhere to specific safety and performance standards outlined in IEC 80601-2-78, safeguarding all users involved.

2.5 Ease of Handling and Maintenance

Medical robots are designed to be user-friendly, allowing healthcare professionals without technical backgrounds to operate them effectively. This user-centric design necessitates straightforward architecture, easy handling, and quick maintenance protocols to ensure the robots' longevity and reliability. These robots assist in various patient care tasks, including the use of prosthetic limbs, orthoses, and auditory and visual aids, all requiring minimal maintenance.

2.6 Power Requirements

The continuous operation of medical robots is dependent on a reliable supply of power, which must be consistently available, whether AC or DC. Given the variety of healthcare facilities, from urban hospitals to remote field hospitals, the integration of renewable energy sources ensures uninterrupted power. Furthermore, developments in wireless power transfer technologies are enhancing the operational efficiency of mobile robots, reducing the need for frequent recharging.

2.7 Cost Implications

Affordability is key in the widespread adoption of robotic solutions in healthcare, particularly in making these technologies accessible globally, including in developing countries. While surgical robots represent a high-cost investment due to their advanced technology and integrated systems for precise tool manipulation, it is crucial for the scalability and affordability of these systems to be considered to ensure they can serve a broad range of healthcare needs worldwide. A comprehensive literature search was executed across multiple databases including PubMed, Science Direct, Scopus, and EMBASE. The search strategies, developed individually by the review authors, were refined and unified through group discussions. We employed a dual-level classification of search terms: the first level included terms related to healthcare like "hospital", "medic", "pharmaceutic", and the second level included drone-specific terms like "Unmanned aerial vehicle" and "Urban air mobility". We systematically explored all possible combinations of these terms across the databases. The articles retrieved were scrutinized based on well-defined inclusion criteria focusing on the design, development, or evaluation of drone-integrated healthcare services. Articles were excluded if they primarily addressed other uses, such as search-and-rescue missions, unless the drones also played a role in medical support like triage or diagnosis. Articles illustrating drones as one of many technological applications without specific emphasis on healthcare were also omitted.

III. EXPLORING THE ROLES OF ROBOTS IN HEALTHCARE SETTINGS

In the ever-evolving landscape of healthcare, robots have carved out significant niches, performing a variety of tasks across different areas. The deployment of robots in healthcare can be grouped into several categories based on their functions and areas of operation. These include zones designated for receptionist robots, nurse robots, ambulance robots, telemedicine robots, service robots within hospitals, cleaning robots, disinfection robots, surgical robots, radiologist robots, rehabilitation robots, culinary robots, and robots tasked with outdoor deliveries.

3.1. Receptionist Robots

Positioned typically at the entrance of hospitals, receptionist robots play a crucial role in managing the flow of information and visitors. These robots are particularly adept at welcoming guests, providing details about the hospital's departments, and navigating people to their desired destinations, as illustrated in Figure 4. Capable of handling a high volume of visitors tirelessly, these robots efficiently direct individuals to their chosen physicians [31]. They also engage with young visitors, captivating children with their interactive features, thus easing their discomfort and making their hospital visit a more pleasant experience.

Figure 4. Receptionist robots in hospitals for patient assistance. (**a**) Pepper robot in a Belgian hospital [**29**]. (**b**) Dinsow 4 robot [**30**].

3.2 Nurse Robots in Hospitals

Nurse robots have been introduced in hospitals to support doctors similarly to how human nurses would. These robotic aides are particularly prevalent in Japan, a country noted for having the highest proportion of elderly people over the age of 75 among OECD nations. This demographic trend presents a significant challenge to Japanese healthcare facilities, which struggle with adequate staffing for elderly care. As a result, many Japanese find themselves obligated to care for their aging relatives at home, which often prevents them from maintaining regular employment [32]. Furthermore, healthcare professionals in Japan face considerable stress and fatigue due to the high number of patients they must manage. In response to these pressing issues, the Japanese government is increasingly turning to technological innovations. These robotic solutions are designed to assist in the care of elderly patients, thereby alleviating some of the burdens on human staff, as illustrated in Figure 5.

Figure 5. Nursing robots in hospital and at home for elderly care. (**a**) Robear—a robotic bear nurse to lift patients in Japan [**33**]. (**b**) Dinsow robot for elderly entertainment and face-to-face calls [**34**]. (**c**) Moxi—nursing robot placing medicines in bins [**35**]. (**d**) Robot attendant for hospital care [**36**].

The future of nursing in Japan may see humanoid nursing robots (HNRs) stepping in to perform many tasks traditionally handled by human nurses. These robots are increasingly utilized because they can provide around-the-clock services at considerably lower costs [37]. In Japan, robots like Paro from AIST in Toyama, Pepper from Softbank Robotics in Paris, and Dinsow from CT Asia Robotics in Bangkok are already aiding elderly patients. They help not just with physical tasks like lifting but also offer therapeutic assistance. Each of these robots has become an integral part of the Japanese healthcare system [38]. Dinsow, for instance, includes features specifically designed to aid patients with Alzheimer's. It can display photos of various people and prompt the patient to associate each face with the correct name, which is a technique used to alleviate symptoms of dementia [34]. Despite these innovations, the acceptance of such service robots varies significantly from one country to another. Furthermore, while HNRs are proving their worth, some elderly patients still emphasize the irreplaceable value of human interaction. They believe that while robots are helpful, the compassionate presence of human staff remains crucial in healthcare. Additionally, Table 1 details a range of medical robots and their applications, showcasing the breadth of robot use in modern medicine.

Robot	**Make**	**Cleaning**	**Nursing**	**Pharmacy**	**Lab**	**Food Service**	**Waste Removal**	**Linen**
Dinsow	CT Asia Robotics (Thailand)		✓					
Relay	Swisslog (Switzerland)			✓	✓	✓	✓	✓
TUG	Aethon (USA)		✓	✓	✓	✓	✓	✓
RP-VITA	iRobot (USA)		✓					
Roomba i7	iRobot (USA)	✓						
Moxi	Diligent Robots (USA)		✓	✓				
Ambubot	Thailand		✓	✓				
Drone Robot	TU Delft (Netherlands)		✓	✓				

3.3. Humanizing Emergency Response with Ambulance Robots

Every year, approximately 800,000 individuals across the European Union (EU) experience cardiac arrest, but tragically, only 8% survive this dire emergency [39]. This alarming statistic underscores the urgent need for swift medical intervention. The primary culprit behind the high fatality rate is the delayed response time of traditional emergency services, which typically take around 10 minutes to arrive. However, the window for effective treatment is much narrower, with irreversible brainstem death setting in just 4–6 minutes after a severe cardiac event [40]. The importance of rapid response becomes even more evident when considering the critical moments following an accident. Swift medical attention can prevent the escalation of injuries and significantly increase the chances of survival and recovery [41]. This is especially true for conditions such as drowning, cardiac arrest, shocks, and respiratory distress. To address this pressing need, innovative solutions leveraging cutting-edge technology are emerging. One such solution involves the use of ambulance robots, which are capable of delivering life-saving interventions with minimal response time. These robots can be deployed swiftly to reach both mobile and remote patients in need of urgent medical assistance [39]. By leveraging advancements in drone technology, essential medical supplies can be transported swiftly to the scene of an emergency.

Figure 6a and 6b illustrate the versatility of these ambulance drones in providing timely emergency care. Developed by TU Delft in the Netherlands, these drones boast a lightweight and compact design, allowing them to carry vital medical equipment for immediate life support [40]. A notable feature of these drones is their ability to transport Automated External Defibrillators (AEDs), as depicted in Figure 6c. These early prototypes represent a promising step towards revolutionizing emergency response systems and saving countless lives in the process.

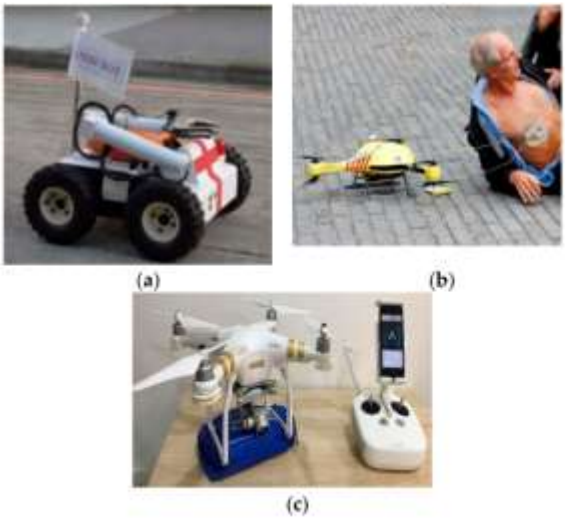

Figure 6. Ambulance robots. (**a**) Ambubot [**39**]. (**b**) Automated External Defibrillator (AED) for patient recovery [**40**]. (**c**) Drone carrying a first aid kit (blue) controlled by a smart phone [**41**].

3.4 Telemedicine Robots

Telemedicine robots play a crucial role in healthcare, particularly through their applications in remote medical consultations. These robots enable doctors to assess patients' physiological parameters and diagnose diseases from afar using audiovisual tools [42]. This technology proves particularly invaluable during widespread infectious epidemics in isolated regions where access to hospitals and medical professionals is limited.

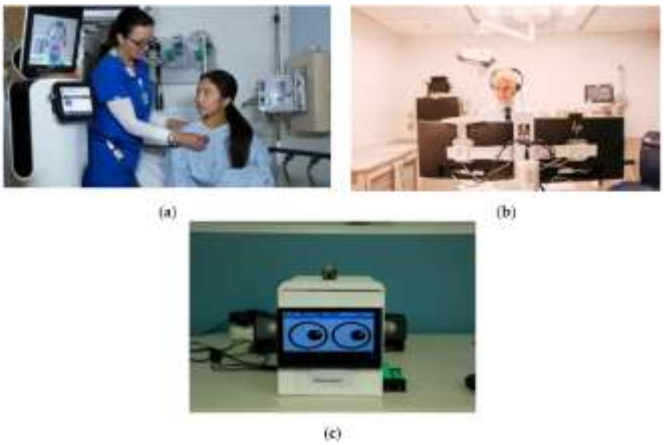

Figure 7. Telemedicine Robots for real-time remote patient assistance. **(a)** RP-VITA: FDA approved first autonomous telemedicine robot [**43**]. **(b)** Dr. Paul Casey, taking video calls at Rush University Medical Center [**44**]. **(c)** Doctor Robot for telemedicine [**45**].

For instance, depicted in Figure 7a is RP-VITA, developed by MedTech Boston, MA, USA, which holds the distinction of being the first autonomous telemedicine robot approved by the FDA. This robot allows physicians to communicate with patients through real-time audiovisual teleconferencing, as illustrated in Figure 7b. Additionally, the telemedicine robot shown in Figure 7c facilitates a cost-effective remote interaction for diagnosing various health conditions, demonstrating the versatility and importance of these systems in modern healthcare.

3.5. Utilizing Service Robots in Hospitals

Hospitals are bustling environments where a variety of tasks, particularly those involving the movement of materials, are crucial. These include duties that require significant effort, such as pushing and pulling heavy loads. Service robots are increasingly being employed to handle these demanding tasks efficiently [46]. Their roles extend beyond mere heavy lifting; robots are revolutionizing how care is delivered in hospitals. They play a vital part in enhancing patient care by undertaking responsibilities like delivering meals to patients [47], handling food and beverages, and managing the distribution of medications. Additionally, these robots contribute to maintaining cleanliness and hygiene in healthcare settings. They are tasked with the removal of soiled laundry and the distribution of fresh bed linen, ensuring that patient areas remain sanitary and comfortable. Moreover, service robots are instrumental in the safe transportation of both regular and hazardous waste within the hospital premises. This multifaceted deployment of robots not only optimizes operational efficiency but also supports essential health and safety standards, as illustrated in Figure 8 below.

Figure 8. Indoor serving robots in hospitals. (**a**) Chinese hospitals using robots to deliver medicines in a patient's room [**48**]. (**b**) Panasonic Autonomous Delivery Robots—HOSPI—deployed in a hospital in Singapore [**49**]. (**c**) TUG autonomous service robot [**50**]. (**d**) RELAY robot to deliver medicine [**51**]. (**e**) LoRobot L1 [**52**].

3.6. Cleaning Robots in Healthcare Settings

In the realm of healthcare, the use of robots for cleaning tasks represents a significant leap forward, marrying technology with hygiene. These robots, equipped with capabilities such as dry vacuuming and mopping, are revolutionizing the way hospitals maintain cleanliness and control infections. Such technological advancements align with the early visions of innovators who saw great potential in robots beyond industrial applications. These robots play a crucial role in hospital sanitation efforts, aiming to eradicate harmful germs and contaminants effectively. Illustrations of these robots can be seen in various figures. For instance, the Roomba cleaning robot, developed by iRobot in Bedford, Massachusetts, USA, showcases its prowess in both dry and wet mopping. This is intelligently depicted in Figure 9a. Similarly, the UVD robot from UVD Robots ApS in Odense, Denmark, utilizes ultraviolet radiation to disinfect hospital environments, eliminating microbes efficiently as shown in Figure 9b. Additionally, the Peanut robot, originating from San Francisco, USA, demonstrates its utility in cleaning hospital washrooms through a sophisticated robotic gripper and sensing technology, as illustrated in Figure 9c. Lastly, the Swingobot 2000 by TASKI in South Carolina, USA, is highlighted in Figure 9d as a robust solution for autonomously cleaning hospital floors, emphasizing its heavy-duty capabilities.

Figure 9. Cleaning and mopping robots in hospitals. (**a**) Roomba i7 cleaning robot [**54**]. (**b**) UVD robot for disinfecting hospital premises [**55**]. (**c**) Peanut robot for washroom cleaning [**56**]. (**d**) Swingobot 2000 cleaning robot [**57**].

3.7. Use of Spraying and Disinfestation Robots

Robots equipped for spraying and disinfestation play a crucial role in maintaining hygiene and safety in expansive outdoor settings, such as city residential centers. These robots are specifically designed to administer antiseptic solutions over wide areas. To ensure the safety of the operators and to minimize human exposure to potentially hazardous chemicals, these robots are operated remotely. For instance, as illustrated in Figure 10a and 10b, sanitation workers can be seen using scooters to maneuver these robots. This setup allows them to effectively and safely disinfect public spaces and surroundings.

Figure 10. Spraying and sanitizing robots in residential areas of China [**58**]. (**a**) Remote control disinfecting mobile robot in Hangzhou, China. (**b**) Spraying robots to disinfect large residential areas in China. (**c**) A hand sanitizer-dispensing robot in Shanghai.

3.8. Surgical Robots

Surgical robots have revolutionized the field of medicine by enabling minimally invasive surgery (MIS) with a level of precision and accuracy that surpasses traditional methods performed by human surgeons. These advanced machines, often referred to as tele-operators, are specifically designed to facilitate surgeries remotely. A notable example of this technology is the Da Vinci robotic surgical system, developed by Intuitive Surgical Inc. This system has gained widespread recognition for its effectiveness and has become a staple in modern surgical procedures, as illustrated in Figure 11.

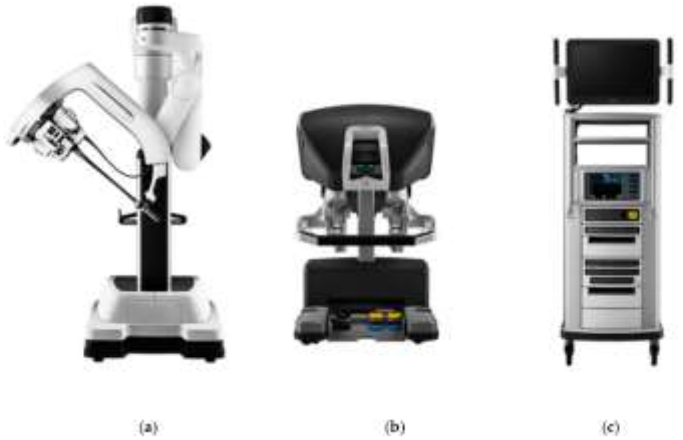

Figure 11. Da Vinci robotic surgical system [**60**]. (**a**) Patient cart. (**b**) Surgeon console. (**c**) Vision cart.

In the current landscape of medical innovation, the fourth-generation Da Vinci surgical systems, developed by Intuitive Surgical in California, are transforming minimally invasive surgery (MIS) through their sophisticated yet user-friendly mechanisms. These systems are not only equipped with complex machinery that performs delicate procedures with simple, precise movements, but they also feature an upgradable design. This adaptability allows for various configurations to suit different surgical needs, accompanied by a reliable interface that enhances the surgeon's control and interaction, as illustrated in Figure 12. Moreover, the Da Vinci systems support the standardization of instruments and components. This standardization is crucial for hospitals as it simplifies the management of inventories and boosts operational efficiency, as noted in reference [60]. These innovations underscore the ongoing advancements in surgical technology, promising improved outcomes and streamlined processes in healthcare settings.

Figure 12. Real time surgery via HD vision using Da Vinci robotic surgical system [**61**]. (**a**) Surgeon remote manipulation. (**b**) Patient being operated by robotic hands.

3.9. The Advent of Radiologist Robots

Radiology represents a critical field where robotic technology is increasingly utilized, primarily due to the significant radiation exposure that can pose risks to human operators. A notable innovation in this area is the Twin Robotic X-ray system developed by Siemens Healthineers, based in Henkestr, Germany. This system is a breakthrough in medical imaging technology, integrating capabilities like fluoroscopy, angiography, and 3D imaging, as illustrated in Figure 14a [65]. The Twin Robotic X-ray system offers a significant advancement over traditional methods by allowing a multitude of X-ray procedures to be conducted in a single room. This is made possible because the robot can move around the patient, who remains stationary, providing real-time 3D images to physicians. Traditional 2D X-rays often fall short in detecting subtle abnormalities, such as hairline fractures in bones, which typically require confirmation through computed tomography (CT) scans.

However, with the Multitom Rax Twin Robotic X-ray system, it's possible to obtain a 3D image on the same machine, thus bypassing the need for a separate CT scan. This capability not only simplifies the diagnostic process but also enhances the efficiency and safety of radiological procedures, safeguarding both patient and medical staff from unnecessary radiation exposure.

Figure 14. Specialized robots for spine and cranial biopsy and surgery. (**a**) Multitom Rax: Twin Robotic X-ray from Siemens Healthineers [**65**]. (**b**) Cyberknife: Radiology Oncology Surgical robot [**66**].

The Cyberknife system, a highly sophisticated robotic platform developed in Sunnyvale, USA, is utilized in the treatment of cancer through radiotherapy, as illustrated in Figure 14b. This technology specializes in delivering two types of treatments: stereotactic radiosurgery (SRS) and stereotactic body radiation therapy (SBRT). It boasts remarkable capabilities in precision, thanks to its robotic technology and integrated real-time motion synchronization, ensuring targeted and effective treatment across various parts of the body [66].

3.10. Rehabilitation Robots

Rehabilitation robots play a crucial role in aiding the recovery of patients who have suffered from incidents such as accidents or strokes [27]. These robots are not only instrumental in supporting those with disabilities and the elderly, but they also improve conditions for individuals facing various physical challenges. By fostering the functional reorganization of the nervous system, these robots significantly help in reducing muscle atrophy and enhance overall motor function [67]. Consequently, this technology alleviates the physical burden on rehabilitation staff, thereby enhancing the efficiency of healthcare services. Among the notable examples are the Kinova assistive robot, made by Kinova Robotics in Boisbriand QC, Canada, which aids patients in handling objects through its multi-degree-of-freedom performance and can be controlled via a brain-computer interface (BCI). Additionally, the EksoNR, developed by Ekso Bionics in Richmond, USA, is an exoskeleton designed to improve the mobility of individuals with disabilities [68]. For instance, depicted in Figure 7a is RP-VITA, developed by MedTech Boston, MA, USA, which holds the distinction of being the first autonomous telemedicine robot approved by the FDA. This robot allows physicians to communicate with patients through real-time audiovisual teleconferencing, as illustrated in Figure 7b. Additionally, the telemedicine robot shown in Figure 7c facilitates a cost-effective remote interaction for diagnosing various health conditions, demonstrating the versatility and importance of these systems in modern healthcare.

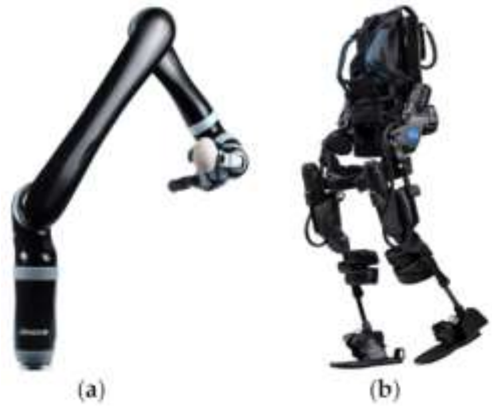

Figure 15. Rehabilitation and assistive robots. (**a**) Kinova assistive robotic arm [**69**]. (**b**) EksoNR exoskeleton [**70**].

3.11. Food Robots in Healthcare Settings

In modern hospitals, robots are becoming essential members of kitchen and pantry teams, helping ensure that the food served is not only delicious but also meets the highest hygienic standards. These robotic systems, engineered with precision, span a range of functions from cooking to serving, reflecting the innovative spirit of roboticists.

For example, some hospitals in France have adopted robot chefs, like the one illustrated in Figure 16a, to assist in meal preparation. Similarly, robots are also being utilized to serve food in hospital restaurants, as depicted in Figure 16b. In the United States and the United Kingdom, advancements in robotic technology have led to the creation of sophisticated cooking robots like Cooki and Moley. Cooki, developed by Sereneti Kitchen in Atlanta, Georgia, features a single robotic arm and is showcased in Figure 16c. On the other hand, Moley Robotics in London has introduced a more complex model with two robotic arms, presented in Figure 16d. These innovations highlight a significant leap forward in how culinary processes are automated in healthcare environments, ensuring efficiency and adherence to safety standards [8][71][72].

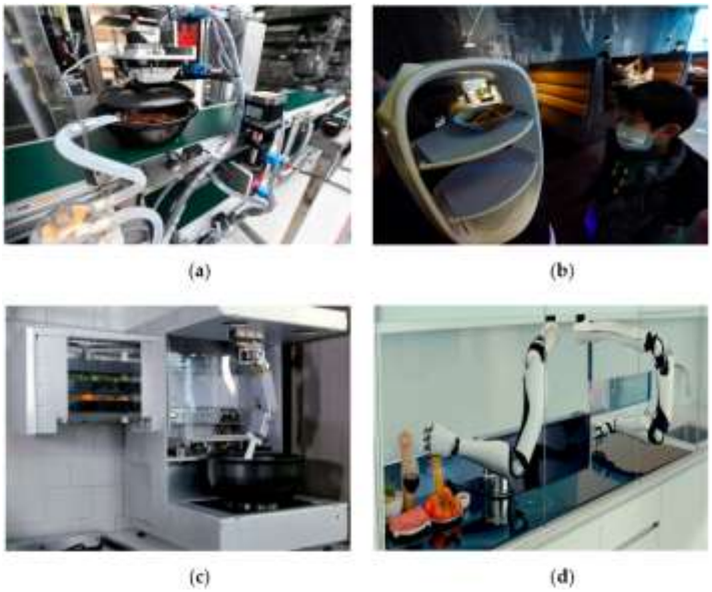

Figure 16. Food robots in a hospital's kitchen for preparing and delivery. (**a**) Robot chef in a France hospital [**58**]. (**b**) Food delivery robot in hospital [**58**]. (**c**) Cooki robot to prepare meals [**71**]. (**d**) Moley—World's first robotic kitchen [**72**].

3.12 Outdoor Delivery Robots

Outdoor delivery robots represent a significant advancement in healthcare logistics, especially in the transportation and delivery of essential medical supplies like drugs and blood samples to and from hospitals. These robots are designed to operate autonomously, whether they navigate on the ground or fly through the air. Some models also support man-in-the-loop operations, allowing remote control by an operator from a distance. This flexibility in operation ensures that they can adapt to various environments and requirements. One notable example of such technology is the drone delivery systems developed by Flirtey, based in Reno, Nevada, USA. Flirtey's drones are not just about efficiency; they are crafted with the vision of saving lives and enhancing lifestyles by revolutionizing the speed and accessibility of delivery services. This approach is illustrated in the deployment scenarios shown in Figure 17a [73], highlighting how these robots can be a game-changer in medical and emergency situations by delivering instant help.

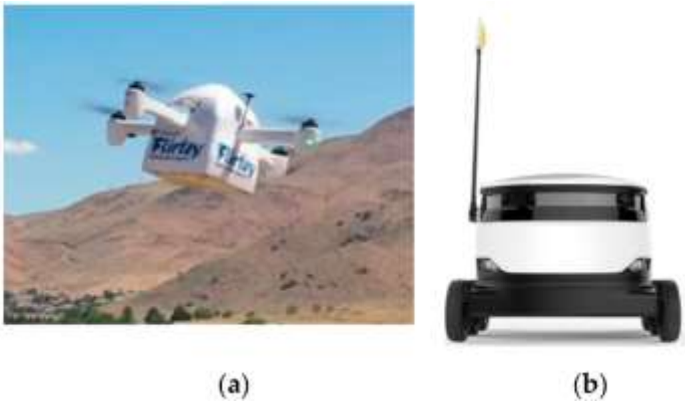

Figure 17. Outdoor delivery robots (ground based and aerial systems). (**a**) Flirtey drone robot for delivery of medicine/blood sample/food [**73**]. (**b**) Starship autonomous delivery robot [**74**].

Starship Technologies, based in San Francisco, USA, has developed innovative ground-based delivery robots capable of transporting items weighing less than 100 pounds within a 4-mile radius, as depicted in Figure 17b. These robots are adept at delivering a range of items such as medicines, parcels, groceries, and food, all sourced directly from pharmacies and stores based on orders placed through a customer's mobile app. Once an order is placed, the customer can track the robot's route and current location via their smartphone. To enhance security during transit, the robot's cargo bay is equipped with an electromechanical lock, which remains engaged until delivery. The recipient can then unlock the cargo bay using the same smartphone app to securely retrieve their items [74]. Table 2 offers an informative overview of major medical robots, detailing their specific applications, technical specifications such as weight, dimensions, nominal payload, operational duration, maximum speed, and the countries where they are manufactured. This table serves as a valuable resource for understanding the diverse capabilities and design features of these advanced robotic systems.

Table 2. Comparison of various medical robots and their specifications.

Title	**Application**	**Weight [kg]**	**Dimension [m^3]**	**Nominal Payload [kg]**	**Operation duration [hr]**	**Max Speed [m/s]**	**Origin**	**Ref**
RELAY	Service	40.8	0.021	4.5	4	0.7	Swisslog, Switzerland	[**51**]
TUG (T3 XL)	Service	635	1.034	-	10	0.76	Aethon, USA	[**50**]
HOSPI	Service	170	0.633	20	9	1.0	Panasonic, Singapore	[**49**]
RP-VITA	Telemedicine	79.37	0.565	-	4–5	Pan: 90 °/s Tilt: 60 °/s	iRobot, USA	[**43**]
Roomba i7	Cleaning	3.37	0.01	0.37	1.25	0.3	IRobot, USA	[**54**]
LG HOM-BOT	Cleaning	3.17	0.0086	0.5	1.75	0.35	LG, South Korea	[**75**]
KINOVA GEN3	Assistive	7.2	902 mm (max reach)	2.0	-	0.5	KINOVA, USA	[**69**]
EksoNR	Assistive	25	-	100	1	Variable	Ekso Bionics, USA	[**70**]
Mazor X	Spine Surgery	6.9	0.012	-	-	-	Medtronic, USA	[**76**]
Swingobot 2000	Cleaning	252	1.56	90	4	0.62	Diversey Inc, USA	[**57**]
Cyberknife	Radiosurgery	1267	1.01	240	-	-	Accuracy, USA	[**66**]
LoRobot L1	Service	200	0.84	100	8	1.2	Hills, South Korea	[**52**]

IV. PERSPECTIVES ON MANAGING COVID-19

Recent studies have highlighted that the majority of COVID-19-related deaths predominantly affect the elderly, particularly those with underlying health conditions, as detailed in Table 3 and Table 4. In response to the pandemic, the Centers for Disease Control and Prevention (CDC) has developed a set of guidelines aimed at effectively managing COVID-19 patients. These critical guidelines can be found in references [77,78]. This strategic approach helps healthcare providers to tackle the challenges posed by the virus more efficiently, ensuring that the most vulnerable populations receive the best possible care.

Table 3. Age related case fatalities of COVID-19 [**79**].

Patient Age	**Case Fatality**
30–39	0.2%
40–49	0.4%
50–59	1.3%
60–69	3.6%
70–79	8%
≥80	14.8%

Table 4. Comorbid case fatalities of COVID-19 [**79**].

Comorbidities	**Case Fatality**
Cardiovascular disease	10.5%
Diabetes	7%
Chronic respiratory failure	6%
Hypertension	6%
Cancer	6%

To effectively manage resources and protect both staff and patients during the COVID-19 pandemic, healthcare facilities must implement specific measures:

(a) Hospitals and clinics should focus on urgent and emergency visits to conserve resources for combating COVID-19. It's crucial to postpone all elective and non-urgent admissions until the situation stabilizes.

(b) It is vital to conserve personal protective equipment (PPE) and other medical supplies. These resources are essential to ensure the safety of healthcare workers and patients alike.

(c) Routine appointments for dental and eye care should be deferred to prevent unnecessary exposure and conserve medical supplies.

(d) Elective surgeries and other non-essential medical procedures should be delayed, allowing healthcare facilities to dedicate more resources and attention to patients affected by COVID-19.

(e) Elderly patients, especially those with pre-existing conditions, are at a significantly higher risk of severe complications from COVID-19 compared to younger individuals.

(f) Individuals with chronic health issues and pregnant women are also at increased risk of severe outcomes if they contract the virus.

(g) Patients exhibiting mild symptoms of COVID-19 may not need to be hospitalized immediately. Home isolation can be considered to prevent the spread of the virus within healthcare facilities.

(h) However, any patient showing signs of deterioration, particularly with symptoms that suggest progression to the lower respiratory tract in the second week of the illness, should be closely monitored.

(i) The choice between inpatient and outpatient care for a patient should be guided by their specific clinical symptoms and overall health condition.

(j) The incubation period for COVID-19 is generally around four days, although it can range from 2 to 14 days. This variability is based on what is known from other coronaviruses like MERS-CoV and SARS-CoV, and it underscores the need for flexible patient monitoring protocols.

4.1. Clinical Presentation

Patients hospitalized with COVID-19 typically present symptoms such as fever, cough, shortness of breath, and fatigue. While fever is the most common symptom among these patients, other respiratory symptoms can include a sore throat and cough with sputum production. Some patients might also experience gastrointestinal issues before the onset of fever and lower respiratory symptoms.

Table 5. COVID-19 patient’s reported symptoms [**77**].

Symptoms	**Percentage**
Fever	77–98%
Cough	46–82%
Myalgia or fatigue	11–52%
shortness of breath	3–31%

4.2 Diagnostic Testing

Diagnostic tests play a crucial role in identifying COVID-19 among patients. Medical professionals collect samples from the nasal region to test for the virus. The preferred method for capturing the state of upper respiratory infections involves nasopharyngeal (NP) specimens. For more severe cases, samples from the lower respiratory tract, such as lung biopsies, prove valuable. Furthermore, analyzing serum helps in tracking the presence and quantity of antigens and antibodies in individuals battling COVID-19. In many cases, CT scans of the chest reveal that the virus typically affects both lungs [76]. Currently, there are no specific treatments for COVID-19. Therefore, the primary approach involves preventive measures, managing symptoms, and controlling complications. In certain severe scenarios, patients might require advanced organ support based on their medical needs [78]. A handful of antiviral medications, such as Remdesivir and chloroquine, have shown effectiveness against the SARS-CoV-2 virus in studies [80, 81]. Additionally, extensive efforts are ongoing to develop a vaccine to combat the COVID-19 virus. Individuals diagnosed with this virus are advised to undergo isolation either in medical facilities or at home for a period of two weeks to prevent the spread of the infection.

4.3 Case Study—COVID-19 Wuhan, China

In response to the COVID-19 outbreak, the Chinese health authorities implemented rigorous measures to manage and contain the disease effectively in Wuhan, the initial epicenter. Among these measures was the innovative use of robotic technology to administer and control the spread of the virus. This approach is illustrated in Figures 18 and 19, showcasing how technology was integrated into the public health strategy to combat the epidemic.

Figure 18. Robots in action during the COVID-19 epidemic in China [**82**]. (**a**) A patrol robot at a hospital in Shenyang in China's northeastern Liaoning province checking temperatures of people. (**b**) Technicians adjusting disinfection robots in a technological company in Qingdao, east China's Shandong Province.

Figure 19. Reception robots in China during the COVID-19 outbreak. (**a**) Sterilization robot in Wuhan, China [**83**]. (**b**) Reception robot at a hospital ward in Wuhan, China [**84**].

Hospitals have increasingly turned to advanced technology to manage the influx of patients during health crises. Robots, ranging from service robots to those specially designed for disinfection, have played a crucial role. These robotic solutions have significantly limited the transmission of infections to healthcare professionals. In China, during the COVID-19 pandemic, robots were effectively employed at hospital reception areas to initially assess patients for symptoms like flu and fever and to disinfect them right at the entry point. Expert reviews highlight that the swift and strategic responses of the Chinese and Korean governments to the COVID-19 crisis were crucial. By deploying cutting-edge technologies and creating robust guidelines, these governments made significant strides in managing the pandemic. These strategies and guidelines have been shared globally to help other nations combat the spread of COVID-19 and reduce fatalities. The data in Table 3 and Table 4 indicate that the majority of severe cases occurred in elderly patients with pre-existing health conditions. For these vulnerable groups, the use of nursing and telemedicine robots has been particularly beneficial. Additionally, robots have been instrumental in maintaining cleanliness by disinfecting and sterilizing both hospital settings and residential areas. A comprehensive overview of how robotic technologies have been deployed in the fight against COVID-19 is detailed in Table 6.

Table 6. Mapping of COVID-19 management steps using robotic solutions.

COVID-19 EDC Recommendation	**Category**	**Prevention**	**Robotics Solution**
Initial contact and assessment	Primary and emergency care	PPE, N95 face mask, goggles, gloves etc.	Robot doctor, Robot nurse, Ambulance robot
Hand hygiene	Personal hygiene	Sterilization	Sanitizer dispensing robot
Surface decontamination	Environmental hygiene	Use of hypochlorite or alcohol based disinfectants e.g., ethanol	Spraying robot for outdoor and UV robots for indoor disinfection
Patient Transport	Ambulance transfer	Surgical mask for the driver, PPE for the accompanying healthcare worker	Self-driving car (SDC) to carry patients
Hospital	Administration measures	PPE, N95 face mask, goggles, gloves etc.	Robot receptionist
	Patient management	as above	Tele-medicine Robot, lifting robot to shift patients from one place to another
	Pharmacy	as above	Medicine dispensing robot, drone robots
	Food services	as above	Robot chef, Food delivery robot
	House keeping	as above	Autonomous service robots
	Environmental Cleaning & waste management	as above	Cleaning/disinfection robots
Lab testing/Imaging	Blood test/sample collection/X-ray	as above	Sampling robot, Biopsy using surgical robot, SDC for sample collection, 3D X-ray and U/S robot
Management of the deceased	Administration measures	as above	Nursing robot for lifting, SDC for transportation to cemetery
Long term care facilities	Palliative Care	as above	Entertainment robots, tele-medicine robot, Nursing robot, Rehabilitation and Assistive robots

V. CONCLUSIONS

This research provides a detailed analysis of how robotics can revolutionize medicine, particularly in the context of managing the COVID-19 pandemic. The effective deployment of robotics in this crisis has shown to substantially lower the rates of infection and death, as observed during the outbreak in China. Given the global scale of this challenge, nations that are technologically advanced have the opportunity to assist others by providing essential robotic technologies and support equipment. This assistance could significantly improve the control and outcomes of the disease worldwide. Our findings reveal that the integration of medical robotics enhances the safety and efficiency of health management systems, marking a significant improvement over traditional manual operations. This is largely due to the advances in healthcare digitization. Medical robots are categorized based on their applications, covering a broad spectrum of hospital services—from robots designed for cleaning to those engineered for complex surgical procedures.

There are numerous avenues for innovation in the design and functionality of medical robots. These include the development of cyber-physical systems (CPS), the optimization of power management with algorithms and renewable energy sources, and the implementation of fault-tolerant controls and dependable architectures. These innovations are essential for ensuring reliable and safe operations within healthcare facilities.

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