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Review

Robotics Applications in the Hospital Domain: A Literature Review

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Abstract: Robotic systems are increasingly being used in healthcare. These systems improve patient care both by freeing healthcare professionals from repetitive tasks and by assisting them with complex procedures. This analysis examines the development and implementation of the use of robotic systems in healthcare. It also examines the application of artificial intelligence (AI), which focuses on the autonomy of robotic systems, enabling them to perform tasks autonomously. It describes the main areas of use of robots in hospitals, gives examples of the main commercial or research robots, and analyzes the main practical and safety issues associated with the use of these systems. Using the main databases, including PubMed, IEEE Xplore, MDPI, ScienceDirect, ACM Digital Library, BioMed Central, Springer, and others, an extensive search for papers related to the topic was conducted. This resulted in 59 papers being identified as eligible for this review. The article concludes with a discussion of future research areas that will ensure the effective integration of autonomous robotic systems in healthcare.

Keywords: artificial intelligence; robot; robotic systems; healthcare; medical technologies

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1. Introduction

The advent of robotic technology, including automated vehicles and factory assistants, is transforming a wide range of industries. It is estimated that around 20% of the world's population is affected by health problems. The adoption of robotic solutions could help bridge the healthcare gap [1]. Human–robot collaboration in healthcare offers promising solutions to the current challenges facing the medical profession. Robots save time and effort for medical teams, increasing efficiency and availability for patients, especially in repetitive tasks.

In this paper, we explore the use of commercially available robots and new research robot projects for the hospital domain. We focus on the main areas where autonomous robotic systems can improve the accuracy, precision, and safety of healthcare activities. In areas such as surgery, transport, and disinfection, there have already been major efforts to produce commercial robots that are already in use in some hospitals. We also address the role that socially assistive robots will have in various therapies where human–robot interaction (HRI) plays a very important role. A good example of a social care robot is PARO, developed by AIST in Japan, which is used in affective therapy sessions [2]. Studies on dementia patients' perception of PARO in the hospital setting suggests potential benefits [3].

The structure of this paper is as follows. Section 2 provides an overview of the methodology used to review the literature and academic studies. Section 3 provides an in-depth examination of the integration of robots, robotic systems, and AI applications in healthcare. It also examines the different areas of healthcare where robots are used, the benefits of automation in hospitals, the infrastructure required for robot functionality in each medical facility, and the challenges and implications associated with robots, robotic systems, AI applications, and related emerging technologies.

Section 4 considers the use of robots and robotic systems in hospital settings, examining the main categories of robots and robotic systems and their applications with illustrative examples. Further, an analysis of the technical specifications, advantages, and disadvantages is also provided. Section 5 considers the potential impact of robots, robotic systems, and AI applications on the future of hospitals. Finally, Section 6 presents a summary of the discussion presented in this article.

2. Methodology for the Literature Review

Given the inherent limitations of the healthcare domain, we endeavored to assess the quality of each potential source by applying methodological rigor to its contribution to the field. To ensure that only impactful and high-quality studies were included in our review, we employed a rigorous process of study selection.

In this review article, we use the following methodology for our research:

- Initial search: An extensive search of prominent databases was conducted, including PubMed, IEEE Xplore, MDPI, ScienceDirect, ACM Digital Library, BioMed Central, Springer, and others.
- The search was divided into three phases. First, based on their titles, we searched databases for papers related to “robotics”, “healthcare”, and “hospital”. This gave a general summary of the volume of research conducted in this area. The records screened equaled n = 936. We then restricted our search.
- Inclusion criteria: The research papers selected were those most relevant to the central themes of this article, namely, (1) the application of robotics in the hospital domain and (2) future prospects for the use of robotics in healthcare and emerging technologies in the context of improving healthcare quality. All the other papers were excluded.

To ensure that the information was up to date, articles published from 2015 onwards were prioritized. The following papers were excluded from the review on the grounds of not meeting the inclusion criteria.

Papers that did not address the application of robotics in the hospital domain: records screened (n = 349), reports not retrieved (n = 290).

Papers that were not related to future prospects for the use of robotics in healthcare and emerging technologies in the context of improving healthcare quality: records screened (n = 120), reports not retrieved (n = 64); 11 duplicated articles were excluded.

Cross-referencing was employed to ensure the inclusion of only the most relevant studies. To expand the scope of our literature review, we also examined the references of the articles analyzed, as well as those of the selected articles, to identify any additional relevant contributions that could enhance the value of our work. The articles included ensure a mix of theoretical research, practical case studies, and academic analyses, providing a comprehensive perspective on the topic (Table 1).

Table 1. Indications of the number of articles from the databases consulted and those that were included in the list of references.

Databases	Found Documents	Documents Excluded	Selected Papers
PubMed	71	51	20
IEEE Xplore	86	74	12
MDPI	49	42	7
ScienceDirect	19	14	5
ACM Digital Library	8	5	3
BioMed Central	5	3	2
Springer	26	24	2
Others	85	77	8
Total	349	290	59

3. Robotics in Healthcare: An Overview

3.1. The Impact of Robotics in Healthcare

The rapid adoption of robotics in response to the global COVID-19 pandemic has highlighted the potential of this technology to reshape many sectors. Robotics is transforming not only surgery and rehabilitation but also emerging fields like telepresence, remote monitoring [3], and personal care tasks [4]. For instance, robots are being utilized in areas not directly connected to clinical practice, such as transporting medications and medical supplies. These autonomous robots can navigate corridors and deliver critical items like medications, biological samples, and medical equipment quickly and accurately [5].

The integration of robots into healthcare teams addresses two significant challenges: the need to care for an aging population and the shortage of qualified healthcare professionals. Moreover, it provides personalized care for diverse needs. The integration of research and industry is a crucial aspect of healthcare. The development and implementation of robotic technologies have the potential to significantly transform the delivery of care, improving both its efficiency and quality [6]. In addition to the technical challenges of implementing robotic solutions, their integration in healthcare requires an in-depth study of the ethical, legal, and social implications.

In the European framework of rights and values, Leenes et al., 2017 [7], address the regulation of emerging robotic technologies by highlighting several key legal and ethical issues [7,8]. In response to these major challenges, the RoboLaw project proposed "Guidelines on Regulating Robotics", which address the regulation of emerging robotic technologies in Europe with respect to the law and ethics [8]. These Guidelines are the result of a collaborative project at the European Commission level, which aimed to explore the ethical, legal, and social implications of the growing use of robots across various sectors of society. In the context of robots operating in hospitals, a set of EU-based health and safety requirements have been defined. Specific regulations have been developed such as the ISO 10218 [9], is a standard defined for robots and robotic devices, Part 1 specifies the safety requirements for industrial robots, while Part 2 specifies the safety requirements for robot systems and integration. Developed by Technical Committee ISO/TC 184, Automation systems and integration, Subcommittee SC 2, in 2011. Which assesses safety risks based on the training level of users interacting with these robotic systems, ensuring safety through control mechanisms like safety inspections and validations, protective measures such as emergency stop buttons, etc. [7,8].

3.2. Applications Across Medical Fields

Hospitals can implement various types of robotic systems to improve efficiency and reduce the risk of human error [1]. Robotic systems are integrated assemblies that include one or more robots together with the control systems, software, and infrastructure required for their operation. These systems are designed to perform complex tasks that require precision and repetitiveness, often replacing or complementing human labor in areas such as surgery, rehabilitation, and hospital logistics [10,11]. Robotics has a wide range of applications in the medical field:

1. Telepresence and Remote Monitoring: robots can be employed to facilitate remote medical consultations, patient monitoring, and remote assistance in cases of limited accessibility or emergencies [3];
2. Transportation: robotic systems are used for the autonomous delivery of medicines, biological samples, and medical supplies within hospitals, thus optimizing logistics and reducing human error [5];
3. Medical Training and Simulation: Robotic simulators are employed to educate medical trainees and healthcare professionals in surgical and diagnostic procedures, providing practical experience in a controlled environment [12].

The examples of robot applications in hospitals show that robots are increasingly being adopted in this context and that there is also a growth in both robotic and emerging technology that can enhance care efficiency and quality [13]. Although most of the investment in robotic research, development, and the production of robots focuses on surgery and rehabilitation, it is necessary to emphasize less explored areas such as cleaning and disinfection in hospitals [1], medical training and simulation, medical diagnosis and imaging, operating theatre assistance, and more. In addition, it is necessary to improve the adaptability of robots in various hospitals contexts, allowing them to operate efficiently in different settings. Improving HRI by developing dynamic algorithms and models that enable evaluation in real-world settings, such as crowded hospital corridors, is crucial [14,15]. Furthermore, it is necessary to expand the capabilities of robotic systems, such as increasing the accommodation capacity, specifically in rehabilitation systems, and making them more adapted to the needs of patients [15]. This development highlights the need for innovative and robust solutions that can support different medical contexts [1,14,16].

3.3. Revolutionizing Hospitals

In the future, robotics will play an important role in the digital transformation of healthcare, and integration will become more profound [17]. Collaboration between humans and robots will be part of everyday work in a hospital, i.e., robots will take part in all tasks and procedures in a hospital context, including cleaning and disinfection, transporting supplies and patients, surgical procedures, etc. [18–20]. The implementation of novel technologies, including robotics and AI applications, has led to a notable improvement in the safety of surgical procedures and a reduction in the length of hospital stays. Autonomous robotic systems (ARSs) are instrumental in hospital logistics, facilitating the management and delivery of supplies. An example of automation and enhanced operational efficacy is the TUG autonomous mobile robot, developed by Aethon. This system, which is already in operational use, facilitates the transport and logistics of materials in hospitals. For example, it is used at St. Olav's Hospital in Trondheim, Norway, where AGVs autonomously transport medicines, samples, supplies, and bed linens. This increases efficiency and reduces the probability of errors [21–23].

An example of the implementation of automated processes and improved operational efficiency in hospitals is the use of the BirthSIM birth simulator, developed by Laerdal Medical, which is now in operation at University Hospital in San Antonio, Texas, to simulate uterine contractions and the mother's voluntary efforts [12]. A further illustration of the benefits of automation and enhanced operational efficiency and quality of care is the deployment of telepresence robots in hospitals. A notable example is the University Hospital in Nancy, France, where the UBBO telepresence robot, AXYN, is remotely operated by the family from a distance and provides the virtual presence of the family within the isolation room of a patient infected with the SARS-CoV-2 virus at the operational stage [23].

4. Robotic Systems in Hospitals Settings

4.1. Surgical Robots

Robotic surgery is a significant application of robotics in the field of medicine. Robotic systems are used to assist in surgical procedures, including minimally invasive surgery [24]. These systems have been developed to overcome the limitations of traditional surgical methods. Robotic-assisted surgery (RAS) technologies, such as the da Vinci Surgical System, have rapidly evolved in recent years. They aim to improve surgical precision, dexterity, and access to minimally invasive procedures [25].

Although autonomous surgery presents ethical, legal, and liability issues, it offers potential benefits, such as increased precision and a reduced risk of human error [26]. Examples of the current state of autonomous robotic surgery and its future potential include the following:

- STAR (Smart Tissue Autonomous Robot), a vision-guided robotic system featuring a powered laparoscopic suturing tool, is currently in the experimental phase. It can perform continuous sutures from image-based commands. The interface supports two modes; manual mode allows the user to specify each stitch's position, and automatic mode enables automatic calculation of each stitch with equal spacing based on the incision´s contour [27].

- The Da Vinci robot with partial automation, although still controlled by humans, is currently in an initial implementation phase. This system allows for the automation of surgical subtasks, leading to the partial automation of certain elements of surgical procedures. This partial automation of certain elements of the surgical procedure enhances safety and precision. The automation process employs AI applications to improve surgical accuracy and targeting [28].
- Robots for ophthalmic surgery such as Preceyes Surgical System, an intraocular robotic surgery system specifically for delicate retinal procedures, are currently in a clinical trials phase. Partial automation, such as pre-programmed movements by the surgeon, allows for more controlled and safer surgical procedures with less risk of human error [29].

4.2. Dentistry Robot Systems

Table 2 provides a comprehensive overview of the dental robots used in hospital settings, comparing them in terms of characteristics, advantages and disadvantages, and stage of development. This comparison includes various robots, like YOMI, Yakebot, and SDI, highlighting their unique features and their impact on patient care [30,31].

Table 2. Summary table of key dentistry robots in hospital settings.

Robot System	**YOMI—Dental Implant Robotic System [30]**	**Yakebot—Dental Implant Robotic System [31]**	**Smart Dental Implant (SDI) Robot System [32]**
Description	Used to aid dental implantation surgery in both the planning and surgical phases (cost ≈ EUR 2.8 M) [30].	Used to perform dental implant surgery (cost ≈ EUR 183 k) [31].	Used for dental implants powered by continuous human oral movement and as a modality of outpatient photo-biomodulation therapy (PBM) [32].
Stage	Research stage [30].	Clinical trial stage [31].	Research and development stage [32].
Features	Provides physical guidance of the depth, orientation and position of the drill, thus avoiding the customized manufacture of surgical guides and the deviation of the operator's hand.	Enables the acquisition of intraoperative feedback information (including tactile and visual information), different surgical methods (automatic drilling and manual drilling), monitoring the position of the patient, and simulating the surgeons' tactile sensations.	It allows light to be supplied in situ, which is made possible by collecting energy from dynamic human oral movements (chewing and brushing) through a designed piezoelectric dental crown, an associated circuit, and light-emitting microdiodes (LEDs).
Advantages	The navigation system provides high predictability and precision in the preparation of dental implant osteotomies using vibrational feedback.	It can perform dental implant surgery under general anesthesia; it can also be performed under local anesthesia, with patients awake but unable to remain completely still throughout the procedure.	It provides a high degree of spatial and temporal control of light emission and adequate mechanical strength like a dental crown. It integrates an energy management circuit that allows energy to be collected.
Disadvantages	Relatively expensive and works under supervision [30].	Complex operation and sharp learning curve [31].	The current method of applying light, such as using an LED probe or optical fiber, usually requires high power or a qualified doctor to establish the interface between the junctional epithelium and the tissue adjacent to the implant abutment [32].

4.3. Rehabilitation Robots

Rehabilitation robots are specially designed machines that help people with physical disabilities during their recovery process. These robots are particularly beneficial for individuals dealing with conditions like stroke, multiple sclerosis (MS), traumatic brain injury (TBI), spinal cord injuries (SCIs), and Spina bifida (SB) [33–36].

In the case of spinal cord injuries, where individuals may face challenges with upper and lower body movements, rehabilitation robots address specific needs. Lower limb rehabilitation robots target leg movements, helping with walking and balance, while upper limb robots focus on arm and hand rehabilitation, helping with tasks such as reaching and grasping objects [36]. Overall, rehabilitation robots play a crucial role in individualizing recovery programs designed by physiotherapists. By targeting specific areas of impairment, these robots can play an important role in aiding patients in regaining their natural motor skills and promoting overall well-being [37].

4.4. Telepresence Robots

The advent of telepresence systems has brought to the fore several challenges currently being faced by healthcare systems and medical personnel across the globe. In this context, robotic-assisted tele diagnosis has emerged as a potential solution, allowing specialist doctors to examine patients remotely [38,39]. The telepresence may be a viable alternative to address the increased demand for healthcare in the elderly population [39]. Table 3 gives a more comprehensive overview of telepresence robots, including examples of practical use, advantages and disadvantages, and the stage of development associated with each telepresence robot system. This can help readers to better understand the clinical and practical implications of these robotic systems in healthcare [23,38].

Table 3. Summary table of key telepresence robot systems in hospital settings.

Robot System	**Double—Autonomous Two-Wheel Video Conferencing Robot [38]**	**UBBO—Telepresence Robot [23]**	**Giraff—Mobile Telepresence Robot [40]**
Description	Used to make remote consultations with patients in different areas of the hospital (cost ≈ EUR 41 k) [38].	Controlled by the family from a remote location and provides a virtual presence for the family of those in isolation rooms (cost ≈ EUR 5 k) [23].	Used to host remote consultation and connect with family when patient cannot leave the room (cost ≈ EUR 11 k) [40].
Stage	Operational stage [38].	Operational stage [23].	Operational stage [40].
Features	Map to target location. Avoiding obstacles. Autonomous navigation.	Enables remote control to remote location. Ensures safety and privacy via daily activity report.	Prioritizes social connection–assistance for elderly individuals who live alone.
Advantages	Facilitates remote communication and collaboration between teams. Allows for more interaction between patients and healthcare professionals.	Autonomous navigation, moving without pre-mapped environments. Follows physical participants. Adjusts height to interact with people of different heights.	Facilitates communication and social contact for isolated individuals or those with limited mobility. Offers a remote assistance solution for caregivers and family members.
Disadvantages	Possible limitations in battery autonomy. Dependency on stable internet connection.	Need technical expertise to operate them. Dependency on stable and high-speed internet connection. Cannot perform some tasks that require human touch.	Accessibility limitations in certain environments or physical spaces. Possible technical challenges for less experienced users.

Telepresence robots may be a viable solution, as some systems can perform simple tasks such as taking patients' vital signs, which could ease the workload of healthcare professionals and carers. There are already several telepresence robotic systems on the operational stage in the market today, including commercial products such as Double Robot, UBBO, and Giraff (Table 3), based on social robotic telepresence functionality [40,41].

4.5. Transportation and Logistics Robots

In the hospital environment, the problem of transport and logistics, in general, relates to the efficient movement of goods and resources such as medical supplies, equipment, laboratory samples, non-medical materials, and patients. This challenge is critical in the sense that any delay or error in the delivery of these items can have serious consequences for the treatment and, consequently, the recovery of patients [42,43]. The use of transport and logistics robots in hospitals, particularly for tasks such as the autonomous movement of goods, has shown significant success. These robots, known as AGVs, not only increase operational efficiency, but also open new possibilities for HRI thanks to their design to promote autonomy and accessibility [42].

The main features of hospital transport robots include load capacity, operational autonomy, precision in navigating hospital corridors, and integration with hospital systems for managing materials and supplies. The ability to operate in complex, high-demand environments such as hospitals is an important differentiator for these robots. Among the advantages of these robots are the ability to operate continuously, without the need for breaks, the precision and consistency of delivery of sensitive materials, and the reduced risk of contamination and cross-infection since they minimize human contact. They can also free operators from repetitive tasks so that they can focus solely on direct patient care [43,44]. However, there are also disadvantages to be considered, such as the high initial cost of implementation, the need for specialized training, and the adaptation of hospital infrastructures to accommodate the new technology.

Table 4 provides a comprehensive overview of the robots employed in logistics and transport systems [22,44,45].

Table 4. Related logistics and transport system robots.

Robot System	**Omron Self-Navigating Autonomous Mobile [46]**	**TUG Intelligent Autonomous Mobile Robot [22]**	**Robotnik RB1—Versatile Autonomous Mobile Platform [44]**
Description	Used in hospitals to optimize internal logistics and improve the efficiency of delivery of supplies, equipment, and other essential materials (cost ≈ EUR 40 k) [46].	Used in hospitals to optimize internal logistics, improve operational efficiency, and ensure a safe and hygienic environment for patients and staff (cost ≈ EUR 13 k) [22].	Used for delivering medications, transporting medical equipment, and removing waste in hospitals. This versatility makes it suitable for a wide range of tasks (cost ≈ EUR 44 k) [44].
Stage	Operational stage [46].	Operational stage [22].	Operational stage [44].
Features	Dynamically move materials in challenging environments: the robot can navigate through complex hospital layouts and adapt to changing environments without manual intervention.	Automatic docking and loading, automatic delivery, removal of trolleys. These features allow the TUG to operate autonomously, reducing the need for human intervention.	Versatile autonomous mobile platform that can be adapted to various logistical tasks in a hospital environment, such as delivering medicines, transporting equipment and materials, collecting waste and laundry, general logistical support, etc.
Advantages	Does not require any modifications: it can be deployed in existing hospital infrastructure without needing significant changes.	Does not require any infrastructure for navigation: can navigate using its built-in sensors, making it easy to implement in various environments.	Modular design allows for easy adaptation to different environments and tasks: can be customized with different modules to handle various tasks, making it highly versatile.
Disadvantages	Integration with other robotic systems can be complex, potentially limiting its use in more advanced automated multi-robot setups.	The robot system can only transport some specific carts, and is not compatible with all types of hospital trolleys.	May require specialized training for operation and maintenance; initial setup costs.

4.6. Cleaning and Disinfection Robots

Hospitals are places where infection prevention is of paramount importance, as the presence of pathogens can lead to nosocomial infections (hospital-acquired infections), which represent a significant risk to patient health. The problem of cleaning and disinfection in hospital environments is complex and multifaceted, requiring an integrated approach that combines strict protocols and ongoing training [47,48]. There are many ultraviolet (UV) germicidal systems available that incorporate specific technological advances. However, the effectiveness and operational status of traditional UV germicidal irradiation (UVGI) systems and robots require continuous improvement, which includes improved UV-C efficiency, better coverage and penetration, automation and mobility, and the incorporation of security features [49].

These robots are widely used in hospital environments for disinfection according to standard procedures and play a crucial role in reducing nosocomial infections [49]. Due to the risks associated with exposure to UV light, it is essential to optimize these robots to ensure safety in areas occupied by patients and healthcare professionals. Although safe operation in the presence of humans requires guaranteeing the secure operation of UVGI robots in areas where patients and healthcare professionals are present, several measures are being implemented with the aim of optimizing the design and functionality of these devices. These include the incorporation of advanced safety mechanisms, including zones of inhibitions, scheduling Incidence analysis, implementation of a personal behavior monitoring system and alerts, and the development of enhanced UV-C control technologies [49]. The use of UVGIs is expected to increase significantly in the post-pandemic era. Remarkable advances have been made to improve the design and use of UVGI systems and robots in hospital and healthcare environments. These advances ensure effective and safe disinfection through technological improvements such as safety mechanisms, 'contactless' disinfection methods, and operational improvements such as Bluetooth and wireless communication. In addition, the possibility of incorporating UVC sensor modules for human–robot co-localization during the UVGI process has been studied, which could lead to the advancement of adjacent UVC sensors to reduce reflections and background radiation [50].

This growth will require more advanced designs for effective and safe disinfection, making hospital environments healthier and more resistant to pathogens [49].

Cleaning and disinfection robots have become essential tools for maintaining safe and sanitized hospital environments, especially in the post-pandemic era, where efficient disinfection is vital for preventing nosocomial infections [49–51]. Table 5 provides a comprehensive overview of the robots used in cleaning and disinfection systems, comparing them in terms of characteristics, advantages and disadvantages, and stage of development.

Table 5. Related cleaning and disinfection robot systems.

Robot System	Xenex Lightstrike High-Intensity Cleaning and Disinfection Robot [49]	Tru-D—Portable UVC Disinfection System [50]	Sterilray—Autonomous Disinfection Vehicle [51]
Description	High-intensity cleaning and disinfection robot used to disinfect patient rooms, surgical areas, and other critical zones (cost ≈ EUR 12 k) [51].	Used mainly for terminal disinfection of bedrooms of patients after discharge or before the admission of new patients (cost ≈ EUR 12 k) [52].	Employed in large and difficult-to-reach areas, such as corridors and common areas, where you can operate it autonomously for continuous disinfection [53].
Stage	Operational stage [49].	Operational stage [50].	Research stage [53].
Features	Integrated sensors have the capacity to interrupt the device when they detect motion and are connected to a network.	Sensor360 technology can calculate the precise UVC dose that is required.	A programmable robotic instrument is a beneficial tool in situations where the quantity of disinfectant required varies.

Table 5. *Cont.*

Robot System	Xenex Lightstrike High-Intensity Cleaning and Disinfection Robot [49]	Tru-D—Portable UVC Disinfection System [50]	Sterilray—Autonomous Disinfection Vehicle [51]
Advantages	Customizable for different room types and positions: Sensors ensure that the operation of the robot is safe in environments where there can be human movement. The customization for different types of rooms allows for flexible and efficient application.	Effectively disinfects a room, including shadowed areas: Sensor360 technology ensures that the UVC dose is accurate, covering even shaded areas, which increases the effectiveness of disinfection.	The high tolerance and performance of Sterilray ADV, along with its ability to operate without human intervention, makes it extremely effective for large-scale disinfection.
Disadvantages	The robot is only a complementary part of the cleaning process and does not replace the need for preliminary manual cleaning.	Only performs terminal disinfections. Limitations include the inability to disinfect surfaces in adjacent rooms, especially in areas such as bathrooms	-

4.7. Social and Assistive Robots

In the healthcare context, for social assistive robotics (SAR)-enabled treatment to be effective, it is essential that the patient trusts both the operator and the robotic system [4]. A good example of trust in an SAR system is the PARO robot, which is used in affective therapy sessions, specifically for patients diagnosed with dementia [52]. Although some research suggests a greater preference for the PARO system over other systems in the same category (NAO and Bandit), there is still no scientific evidence that this PARO system is used in more effective therapy sessions than the other systems (see Hung et al., 2019) [53,54].

This trust is a significant predictor of treatment adherence, satisfaction with treatment, and continuity of care. Trust in the patient–therapist relationship is positively correlated with rehabilitation and treatment outcomes, including pain reduction, improvement in disability, physical and mental health, and satisfaction with treatment. It is therefore crucial to prioritize building trust in the therapeutic relationship, particularly as new technologies such as SAR are integrated into standard care [4].

Table 6 provides a comprehensive overview of the assistive robots used in hospital settings, comparing them in terms of characteristics, advantages and disadvantages, and stage of development. This comparison includes various robots, like PARO, NAO, and Bandit, highlighting their unique features and their impact on patient care [52,54].

Table 6. Summary table of key SAR in hospital settings.

Robot System	PARO—Advanced Interactive Robot [52,54]	NAO—Bipedal Robot [53]	Bandit + Humanoid Robot [54]
Description	Used in dementia care units to calm patients and provide companionship, leading to reduced use of psychotropic medications and improved patient well-being (cost ≈ EUR 55 k) [52,54].	Used in pediatric wards to entertain and distract children during medical procedures, reducing anxiety and stress (cost ≈ EUR 12 k) [53].	Used in physical rehabilitation to assist with exercises, providing encouragement and feedback to enhance effectiveness (cost ≈ EUR 13 k) [54].
Stage	Operational stage. Therapeutic efficacy data are under investigation [52].	Operational stage. Its capacity for evolution is being researched [53].	Research stage [54].
Features	Resembles a baby seal and has sensors for posture, touch, sound, and light.	Humanoid with sensors for movement, touch, sonar, sound, and vision.	Humanoid design, speech, gestures, and facial expressions.

Table 6. *Cont.*

Robot System	PARO—Advanced Interactive Robot [52,54]	NAO—Bipedal Robot [53]	Bandit + Humanoid Robot [54]
Advantages	Reduces anxiety and depression and promotes social interaction.	Versatile, customizable, and engaging.	Interactive, robust design; effective in social therapy.
Disadvantages	Expensive; limited versatility.	Complex operation; expensive.	Cost; complexity.

5. Future Directions

As the autonomy of robotic systems increases, the use of robots in unstructured environments such as hospitals will expand and become more common. Increased adaptability and precision will allow medical procedures to become more personalized and truly tailored to the patient. With the constant integration of different technologies and the use of virtualization tools in the context of healthcare, the metaverse has been proposed [55]. This approach to healthcare makes use of the most advanced technologies that can be applied in the context of digital health, including AI, robotics, quantum computing, IoT, and multi-robot systems. Its integration with advanced automation and decision-making tools can transform the way healthcare services are delivered [2,33,56].

Recent research into autonomous robotic systems as an approach to performing surgery has shown greater precision and reduced accidental movements. These new methods can be used to perform new types of surgery, such as spinal surgery, in addition to benefits associated with post-operative care and calculating patient recovery times [57].

The integration of Virtual Reality (VR) and Augmented Reality (AR) in robotics, especially in the hospital context, has been changing the paradigm of healthcare, specifically in Seetohul [58]. VR and AR are two distinct but interconnected technologies that have the potential to revolutionize healthcare. VR enables access to computer-generated images, providing a simulated reality that can be indistinguishable from the physical world [59]. AR enhances the real-world environment, overlaying the digital one with information from the physical environment [59]. Today, there are advanced surgical robotic systems that exploit the collaboration between robotics and associated AI, VR, and AR technologies by performing pre-programmed repetitive tasks with minimal AI training, in addition to supplementary visual, olfactory, and haptic modalities that have been shown to increase HRI and, therefore, improve overall system performance. Although these systems are still in the early stages of development, it is already possible to have an operating concept based on virtual superposition, which consists of replacing the original view of an object with AR. A good example is the AR-based surgical navigation system called VisAR, developed by Novarad enterprise healthcare solutions; it is in the operational stage, and operates based on the virtual superimposition of organs with submillimeter precision [58].

In addition, visualization and teleoperation can enable complex medical procedures to be carried out remotely, improving access to and the quality of healthcare. However, for these technologies to be effective, it is necessary to develop new, robust, reliable, and secure solutions that can be used in cybernetic design [2]. Furthermore, these solutions must be sustainable and easy to implement [56]. The collaboration of all interested parties, including industry, regulators, professionals, users, legislators, and governments, is essential for creating the necessary infrastructures that will allow these approaches to be implemented in our society [2].

In healthcare, automation can improve the accuracy and efficiency of medical procedures, while multi-robot systems can collaborate in hospital environments to carry out complex tasks. Virtualization and teleoperation can enable the remote execution of surgeries and other critical procedures. Integrating these emerging technologies into hospitals will not only improve the quality of care but will also increase patient safety and reduce operating costs [56,60].

6. Conclusions

The demand for digital healthcare is increasingly evident due to the lack of human resources and the growing pressure on healthcare services. With current developments in robotics and AI and their application to healthcare systems, there is a clear need to make healthcare more resilient, efficient, and competitive. In this article, we examine robotic systems that can be adapted to a healthcare context. Supported by the latest literature on the subject, we investigate the challenges of integrating these systems, considering security and privacy issues, the risk of the dehumanization of healthcare, and the associated ethical and legal concerns. Additionally, our extended research project explores the challenges of deploying more intelligent and autonomous robotic systems in healthcare, such as STAR, partially automated Da Vinci, and VisAR.

These systems, however, face their own challenges due to the limitations of technological maturity. Furthermore, our research involved a comprehensive examination of recent advancements in robotic systems, autonomous robotics, and their applications in the context of contemporary healthcare, with a focus on facilitating efficient, secure, and dependable integration.

We analyzed the potential of robotic systems to enhance the efficiency of treatment, processes, and operations, including systems like PARO, UBBO, and Yomi. These technologies have the potential to revolutionize hospitals, addressing areas such as automation, multi-robot systems, intelligent decision-making, virtualization, and teleoperation.

The integration of VR and AR with robotics is transforming healthcare delivery, particularly in teleoperation and telepresence. Robotics in the metaverse enables the merging of real and simulated data, facilitating augmented clinical trials and remote robotic surgery. Despite these advancements, non-technical issues also pose significant challenges. Financial barriers including the high costs of acquiring and maintaining robotic technologies are a major concern for healthcare providers. Liability issues arising from robotic errors and the need to protect patient privacy further complicate the adoption of these technologies. Moreover, psychological, social, ethical, and legal challenges must be addressed to ensure the responsible use of robots in clinical settings.

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References

1. Shishehgar, M.; Kerr, D.; Blake, J. A Systematic Review of Research into How Robotic Technology Can Help Older People. *Smart Health* **2018**, *7–8*, 1–18. [CrossRef]
2. Morgan, A.A.; Abdi, J.; Syed, M.A.Q.; Kohen, G.E.; Barlow, P.; Vizcaychipi, M.P. Robots in Healthcare: A Scoping Review. *Curr. Robot. Rep.* **2022**, *3*, 271–280. [CrossRef] [PubMed]
3. Hung, L.; Gregorio, M.; Mann, J.; Wallsworth, C.; Horne, N.; Berndt, A.; Liu, C.; Woldum, E.; Au-Yeung, A.; Chaudhury, H. Exploring the Perceptions of People with Dementia about the Social Robot PARO in a Hospi-tal Setting. *Dementia* **2021**, *20*, 485–504. [CrossRef]

4. Langer, A.; Feingold-Polak, R.; Mueller, O.; Kellmeyer, P.; Levy-Tzedek, S. Trust in Socially Assistive Robots: Considerations for Use in Rehabilitation. *Neurosci. Biobehav. Rev.* **2019**, *104*, 231–239. [CrossRef] [PubMed]
5. Huang, R.; Li, H.; Suomi, R.; Li, C.; Peltoniemi, T. Intelligent Physical Robots in Health Care: Systematic Lit-erature Review. *J. Med. Internet Res.* **2023**, *25*, e39786. [CrossRef]
6. Jeelani, S.; Dany, A.; Anand, B.; Vandana, S.; Maheswaran, T.; Rajkumar, E. Robotics and Medicine: A Scien-tific Rainbow in Hospital. *J. Pharm. Bioallied Sci.* **2015**, *7*, S381–S383. [CrossRef] [PubMed]
7. Leenes, R.; Palmerini, E.; Koops, B.J.; Bertolini, A.; Salvini, P.; Lucivero, F. Regulatory Challenges of Robotics: Some Guidelines for Addressing Legal and Ethical Issues. *Law Innov. Technol.* **2017**, *9*, 1–44. [CrossRef]
8. European Comission. *RoboLaw Regulating Emerging Robotic Technologies in Europe: Robotics Facing Law and Ethics*; European Comission CORDIS EU research results; European Comission: Brussels, Belgium, 2015.
9. *ISO 10218-1:2011*; Robots and Robotic Devices—Safety Requirements for Industrial Robots—Part 1: Robots. ISO: Geneva, Switzerland, 2011.
10. AlShamsi, S.; AlSuwaidi, L.; Shaalan, K. Robotics and AI in Healthcare: A Systematic Review. In *Studies in Computational Intelligence*; Springer: Berlin/Heidelberg, Germany, 2022; Volume 1061.
11. Youssef, K.; Said, S.; Alkork, S.; Beyrouthy, T. A Survey on Recent Advances in Social Robotics. *Robotics* **2022**, *11*, 75. [CrossRef]
12. Moreau, R.; Pham, M.T.; Brun, X.; Redarce, T.; Dupuis, O. Simulation of an Instrumental Childbirth for the Training of the Forceps Extraction: Control Algorithm and Evaluation. *IEEE Trans. Inf. Technol. Biomed.* **2011**, *15*, 364–372. [CrossRef] [PubMed]
13. Yang, G.Z.; Cambias, J.; Cleary, K.; Daimler, E.; Drake, J.; Dupont, P.E.; Hata, N.; Kazanzides, P.; Martel, S.; Patel, R.V.; et al. Medical Robotics-Regulatory, Ethical, and Legal Considerations for Increasing Levels of Autonomy. *Sci. Robot.* **2017**, *2*, eaam8638. [CrossRef] [PubMed]
14. Schillinger, P.; Kohlbrecher, S.; Von Stryk, O. Human-Robot Collaborative High-Level Control with Application to Rescue Robotics. In Proceedings of the IEEE International Conference on Robotics and Automation, Stockholm, Sweden, 16–21 May 2016.
15. Kodur, K.; Kyrarini, M. Patient–Robot Co-Navigation of Crowded Hospital Environments. *Appl. Sci.* **2023**, *13*, 4576. [CrossRef]
16. Varlamov, O. "Brains" for Robots: Application of the Mivar Expert Systems for Implementation of Autonomous Intelligent Robots. *Big Data Res.* **2021**, *25*, 100241. [CrossRef]
17. Cresswell, K.; Cunningham-Burley, S.; Sheikh, A. Health Care Robotics: Qualitative Exploration of Key Challenges and Future Directions. *J. Med. Internet Res.* **2018**, *20*, e10410. [CrossRef]
18. Wilk-Jakubowski, G.; Harabin, R.; Ivanov, S. Robotics in Crisis Management: A Review. *Technol. Soc.* **2022**, *68*, 101935. [CrossRef]
19. Piaggio, D.; Zarro, M.; Pagliara, S.; Andellini, M.; Almuhini, A.; Maccaro, A.; Pecchia, L. The Use of Smart Environments and Robots for Infection Prevention Control: A Systematic Literature Review. *Am. J. Infect. Control* **2023**, *51*, 1175–1181. [CrossRef]
20. Vigo, F.; Egg, R.; Schoetzau, A.; Montavon, C.; Brezak, M.; Heinzelmann-Schwarz, V.; Kavvadias, T. An Interdisciplinary Team-Training Protocol for Robotic Gynecologic Surgery Improves Operating Time and Costs: Analysis of a 4-Year Experience in a University Hospital Setting. *J. Robot. Surg.* **2022**, *16*, 89–96. [CrossRef]
21. Tornbjerg, K.; Kanstrup, A.M.; Skov, M.B.; Rehm, M. Investigating Human-Robot Cooperation in a Hospital Environment: Scrutinising Visions and Actual Realisation of Mobile Robots in Service Work. In Proceedings of the DIS 2021—The 2021 ACM Designing Interactive Systems Conference: Nowhere and Everywhere, Virtual, 28 June–2 July 2021; Association for Computing Machinery, Inc.: New York, NY, USA, 2021; pp. 381–391.
22. Sharma, N.; Pandey, J.K.; Mondal, S. A Review of Mobile Robots: Applications and Future Prospect. *Int. J. Precis. Eng. Manuf.* **2023**, *24*, 1695–1706. [CrossRef]
23. Lociciro, A.; Guillon, A.; Bodet-Contentin, L. A Telepresence Robot in the Room of a COVID-19 Patient Can Provide Virtual Family Presence. *Can. J. Anesth.* **2021**, *68*, 1705–1706. [CrossRef] [PubMed]
24. Halder Roy, A.; Ghosh, S.; Gupta, B. Robotics in Medical Domain: The Future of Surgery, Healthcare and Imaging. *Wirel. Pers. Commun.* **2023**, *132*, 2885–2903. [CrossRef]
25. Qian, L.; Wu, J.Y.; Dimaio, S.P.; Navab, N.; Kazanzides, P. A Review of Augmented Reality in Robotic-Assisted Surgery. *IEEE Trans. Med. Robot. Bionics* **2020**, *2*, 1–16. [CrossRef]
26. Han, J.; Davids, J.; Ashrafian, H.; Darzi, A.; Elson, D.S.; Sodergren, M. A Systematic Review of Robotic Surgery: From Supervised Paradigms to Fully Autonomous Robotic Approaches. *Int. J. Med. Robot. Comput. Assist. Surg.* **2022**, *18*, e2358. [CrossRef]
27. Leonard, S.; Wu, K.L.; Kim, Y.; Krieger, A.; Kim, P.C.W. Smart Tissue Anastomosis Robot (STAR): A Vision-Guided Robotics System for Laparoscopic Suturing. *IEEE Trans. Biomed. Eng.* **2014**, *61*, 1305–1317. [CrossRef] [PubMed]
28. Nagy, T.D.; Takacs, M.; Rudas, I.J.; Haidegger, T. Surgical Subtask Automation—Soft Tissue Retraction. In Proceedings of the SAMI 2018—IEEE 16th World Symposium on Applied Machine Intelligence and Informatics Dedicated to the Memory of Pioneer of Robotics Antal (Tony) K. Bejczy, Proceedings, Kosice and Herlany, Slovakia, 7–10 February 2018.
29. Edwards, T.L.; Xue, K.; Meenink, H.C.M.; Beelen, M.J.; Naus, G.J.L.; Simunovic, M.P.; Latasiewicz, M.; Farmery, A.D.; de Smet, M.D.; MacLaren, R.E. First-in-Human Study of the Safety and Viability of Intraocular Robotic Surgery. *Nat. Biomed. Eng.* **2018**, *2*, 649–656. [CrossRef] [PubMed]
30. Ahmad, P.; Alam, M.K.; Aldajani, A.; Alahmari, A.; Alanazi, A.; Stoddart, M.; Sghaireen, M.G. Dental Robotics: A Disruptive Technology. *Sensors* **2021**, *21*, 3308. [CrossRef]
31. Liu, C.; Liu, Y.; Xie, R.; Li, Z.; Bai, S.; Zhao, Y. The Evolution of Robotics: Research and Application Progress of Dental Implant Robotic Systems. *Int. J. Oral Sci.* **2024**, *16*, 28. [CrossRef] [PubMed]

32. Park, M.; Islam, S.; Kim, H.E.; Korostoff, J.; Blatz, M.B.; Hwang, G.; Kim, A. Human Oral Motion-Powered Smart Dental Implant (SDI) for In Situ Ambulatory Photo-Biomodulation Therapy. *Adv. Healthc. Mater.* **2020**, *9*, 2000658. [CrossRef] [PubMed]
33. Kyrarini, M.; Lygerakis, F.; Rajavenkatanarayanan, A.; Sevastopoulos, C.; Nambiappan, H.R.; Chaitanya, K.K.; Babu, A.R.; Mathew, J.; Makedon, F. A Survey of Robots in Healthcare. *Technologies* **2021**, *9*, 8. [CrossRef]
34. Rajavenkatanarayanan, A.; Kanal, V.; Tsiakas, K.; Calderon, D.; Papakostas, M.; Abujelala, M.; Galib, M.; Ford, J.C.; Wylie, G.; Makedon, F. A Survey of Assistive Technologies for Assessment and Rehabilitation of Motor Impairments in Multiple Sclerosis. *Multimodal Technol. Interact.* **2019**, *3*, 6. [CrossRef]
35. Ármannsdóttir, A.L.; Beckerle, P.; Moreno, J.C.; van Asseldonk, E.H.F.; Manrique-Sancho, M.T.; del-Ama, A.J.; Veneman, J.F.; Briem, K. Assessing the Involvement of Users During Development of Lower Limb Wearable Robotic Exoskeletons: A Survey Study. *Hum. Factors* **2020**, *62*, 351–364. [CrossRef] [PubMed]
36. Gassert, R.; Dietz, V. Rehabilitation Robots for the Treatment of Sensorimotor Deficits: A Neurophysiological Perspective. *J. Neuroeng. Rehabil.* **2018**, *15*, 46. [CrossRef]
37. Kuroda, Y.; Young, M.; Shoman, H.; Punnoose, A.; Norrish, A.R.; Khanduja, V. Advanced Rehabilitation Technology in Orthopaedics—A Narrative Review. *Int. Orthop.* **2021**, *45*, 1933–1940. [CrossRef]
38. Reyes-Cruz, G.; Phypers, I.; Boudouraki, A.; Price, D.; Fischer, J.; Reeves, S.; Galvez Trigo, M.; Maior, H. Aug-mented Robotic Telepresence (ART): A Prototype for Enhancing Remote Interaction and Participation. In Proceedings of the ACM International Conference Proceeding Series, Nantes, France, 12–15 June 2023.
39. Dorsey, E.R.; Topol, E.J. State of Telehealth. *N. Engl. J. Med.* **2016**, *375*, 154–161. [CrossRef] [PubMed]
40. Takahashi, M.; Ogata, M.; Imai, M.; Nakamura, K.; Nakadai, K. A Case Study of an Automatic Volume Control Interface for a Telepresence System. In Proceedings of the IEEE International Workshop on Robot and Human Interactive Communication, Kobe, Japan, 31 August–4 September 2015.
41. Zhang, G.; Hansen, J.P. Telepresence Robots for People with Special Needs: A Systematic Review. *Int. J. Hum. Comput. Interact.* **2022**, *38*, 1651–1667. [CrossRef]
42. Volland, J.; Fügener, A.; Schoenfelder, J.; Brunner, J.O. Material Logistics in Hospitals: A Literature Review. *Omega* **2017**, *69*, 82–101. [CrossRef]
43. Søraa, R.A.; Fostervold, M.E. Social Domestication of Service Robots: The Secret Lives of Automated Guided Vehicles (AGVs) at a Norwegian Hospital. *Int. J. Hum. Comput. Stud.* **2021**, *152*, 102627. [CrossRef]
44. Ramdani, N.; Panayides, A.; Karamousadakis, M.; Mellado, M.; Lopez, R.; Christophorou, C.; Rebiai, M.; Blouin, M.; Vellidou, E.; Koutsouris, D. A Safe, Efficient and Integrated Indoor Robotic Fleet for Logistic Applications in Healthcare and Commercial Spaces: The Endorse Concept. In Proceedings of the IEEE International Conference on Mobile Data Management, Hong Kong, China, 10–13 June 2019.
45. LD Series Autonomous Mobile Robots | Omron. Available online: https://automation.omron.com/en/mx/products/family/LD (accessed on 15 April 2024).
46. Pedan, M.; Gregor, M.; Plinta, D. Implementation of Automated Guided Vehicle System in Healthcare Facility. *Procedia Eng.* **2017**, *192*, 665–670. [CrossRef]
47. Assadian, O.; Harbarth, S.; Vos, M.; Knobloch, J.K.; Asensio, A.; Widmer, A.F. Practical Recommendations for Routine Cleaning and Disinfection Procedures in Healthcare Institutions: A Narrative Review. *J. Hosp. Infect.* **2021**, *113*, 104–114. [CrossRef]
48. Browne, K.; White, N.; Tehan, P.; Russo, P.L.; Amin, M.; Stewardson, A.J.; Cheng, A.C.; Graham, K.; O'Kane, G.; King, J.; et al. A Randomised Controlled Trial Investigating the Effect of Improving the Cleaning and Disinfection of Shared Medical Equipment on Healthcare-Associated Infections: The CLEaning and Enhanced DisiNfection (CLEEN) Study. *Trials* **2023**, *24*, 133. [CrossRef] [PubMed]
49. Dancer, S.J. Hospital Cleaning: Past, Present, and Future. *Antimicrob. Resist. Infect. Control* **2023**, *12*, 80. [CrossRef]
50. McGinn, C.; Bourke, E.; Cullinan, M.F. An IoT Approach for Monitoring UV Disinfection Robots. In Proceedings of the IEEE International Conference on Systems, Man and Cybernetics, Melbourne, Australia, 17–20 October 2021.
51. Abdi, J.; Al-Hindawi, A.; Ng, T.; Vizcaychipi, M.P. Scoping Review on the Use of Socially Assistive Robot Technology in Elderly Care. *BMJ Open* **2018**, *8*, e018815. [CrossRef] [PubMed]
52. Hung, L.; Liu, C.; Woldum, E.; Au-Yeung, A.; Berndt, A.; Wallsworth, C.; Horne, N.; Gregorio, M.; Mann, J.; Chaudhury, H. The Benefits of and Barriers to Using a Social Robot PARO in Care Settings: A Scoping Review. *BMC Geriatr.* **2019**, *19*, 232. [CrossRef]
53. Nottingham, M.; Peterson, G.; Doern, C.; Doll, M.; Masroor, N.; Sanogo, K.; Stevens, M.; Bearman, G. Ultraviolet-C Light as a Means of Disinfecting Anesthesia Workstations. *Am. J. Infect. Control* **2017**, *45*, 1011–1013. [CrossRef]
54. Valentí Soler, M.; Agüera-Ortiz, L.; Olazarán Rodríguez, J.; Mendoza Rebolledo, C.; Pérez Muñoz, A.; Rodríguez Pérez, I.; Osa Ruiz, E.; Barrios Sánchez, A.; Herrero Cano, V.; Carrasco Chillón, L.; et al. Social Robots in Advanced Dementia. *Front. Aging Neurosci.* **2015**, *7*, 133. [CrossRef]
55. Wang, G.; Badal, A.; Jia, X.; Maltz, J.S.; Mueller, K.; Myers, K.J.; Niu, C.; Vannier, M.; Yan, P.; Yu, Z.; et al. Development of Metaverse for Intelligent Healthcare. *Nat. Mach. Intell.* **2022**, *4*, 922–929. [CrossRef]
56. Chengoden, R.; Victor, N.; Huynh-The, T.; Yenduri, G.; Jhaveri, R.H.; Alazab, M.; Bhattacharya, S.; Hegde, P.; Maddikunta, P.K.R.; Gadekallu, T.R. Metaverse for Healthcare: A Survey on Potential Applications, Challenges and Future Directions. *IEEE Access* **2023**, *11*, 12765–12795. [CrossRef]
57. Zhou, X.Y.; Guo, Y.; Shen, M.; Yang, G.Z. Application of Artificial Intelligence in Surgery. *Front. Med.* **2020**, *14*, 417–430. [CrossRef]

58. Seetohul, J.; Shafiee, M.; Sirlantzis, K. Augmented Reality (AR) for Surgical Robotic and Autonomous Systems: State of the Art, Challenges, and Solutions. *Sensors* **2023**, *23*, 6202. [CrossRef]
59. Singh, D.K.; Kumar, P.; Arora, P.; Sharma, M. A Bibliometric Analysis of Virtual Reality and Augmented Reality Applications in Healthcare. In Proceedings of the International Conference on Artificial Intelligence for Innovations in Healthcare Industries, ICAIIHI 2023, Raipur, India, 29–30 December 2023; Institute of Electrical and Electronics Engineers Inc.: Piscataway, NJ, USA, 2023.
60. Pradyumna, G.R.; Hegde, R.B.; Bommegowda, K.B.; Jan, T.; Naik, G.R. Empowering Healthcare with IoMT: Evolution, Machine Learning Integration, Security, and Interoperability Challenges. *IEEE Access* **2024**, *12*, 20603–20623. [CrossRef]