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Advancing Healthcare Through Intelligent Human-Robot Collaboration: Overview, Challenges and Opportunities

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***Abstract*—Integrating intelligent robots into healthcare environments promises to revolutionise patient care, diagnosis, treatment, and rehabilitation. This paper reviews the current state of Human-Robot Collaboration (HRC) in healthcare, highlighting significant advancements and challenges. It provides a comprehensive overview of critical terminologies and concepts, reviews the latest robotics technologies, and explores their potential to enhance healthcare delivery. Our review reveals substantial opportunities for robots to augment healthcare professionals, improve patient monitoring, and manage repetitive or physically demanding tasks. We also discuss the critical challenges of ensuring patient safety, maintaining privacy and data security, addressing ethical considerations, and overcoming technical limitations such as interoperability and adaptability in diverse healthcare settings. By examining recent studies and innovations, this paper identifies emerging trends and suggests future directions for research and development in HRC within the healthcare sector.**

***Index Terms*—Healthcare, Human-Robot Collaboration, Artificial Intelligence, Assistive Technology, Smart Devices**

I. Introduction

Human-Robot Collaboration (HRC) represents a symbiotic partnership between humans and robots, where both entities work together to achieve common goals. Combining human and robotic abilities is the fundamental notion of HRC [1]. Covering different areas like manufacturing, logistics, and healthcare, HRC is transforming traditional workflows by leveraging each participant's strengths: the creativity, adaptability, and decision-making abilities of humans, alongside the precision, efficiency, and tirelessness of robots. This collaboration increases productivity, improves safety, and enhances overall performance.

This potential comes at a critical juncture in healthcare demographics. Firstly, the COVID-19 epidemic has significantly impacted the psychological state and general wellness of medical practitioners in the United Kingdom [2], primarily attributed to the constant risk of exposure to the virus, the overwhelming daily influx of patients, and understaffing issues. The escalating number of absences among healthcare workers has compromised patient care and services, pushing healthcare facilities to dangerously low staffing levels [3]. Secondly, the World Health Organisation (WHO) projects that, due to demographic shifts, the proportion of people 60 and older will increase significantly globally, from 12% to 22% between 2015 and 2050 [4]. Due to this substantial increase in the population aged 60 and older, there may be a heightened demand for caregivers to provide necessary assistance and support to this demographic. Moreover, by 2030, it is estimated that the worldwide shortage of healthcare workers based on needs will still exceed 14.5 million, representing only a 17% decrease [5]. A global deficit of healthcare professionals, notably nurses and midwives, accounts for over 50% of the current shortfall in healthcare workers [6]. The persistent problem of high turnover and staffing shortages in healthcare has plagued the industry for over a decade [7].

This looming shortage underscores the urgency for innovative solutions like HRC to bridge the gap between healthcare demand and available resources. This paper begins by defining Human-Robot Collaboration (HRC) and examining its importance in healthcare. It then outlines the current trends in integrating HRC within healthcare infrastructure and explores the latest technologies. Lastly, it deliberates on the challenges and emerging trends in this field.

II. Understanding Human-Robot Collaboration in Healthcare

In recent years, the convergence of robotics and healthcare has opened new frontiers in patient care, diagnosis, and treatment. At the centre of this convergence lies the concept of HRC, where intelligent robots work alongside human counterparts to augment capabilities, enhance efficiency, and elevate the standard of care. The collaboration between humans and robots can take on various forms, depending on the configuration of the workspace and the nature of shared tasks. These modalities, encompassing a spectrum of interaction levels, can be classified into five main types, shaping the dynamics of HRC [8].

- **Robot Work Inside the Cell:** The robot operates within a designated enclosure or confined space, maintaining a separate workspace from human interaction. This setup

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ensures safety but limits direct collaboration between the robot and human workers.

- **Coexistence:** Robots and humans work in the same environment but have separate workspaces. They operate together in the workstation, completing different activities independently and together.
- **Synchronised:** A well-designed process allows the robot or the human worker to occupy the workspace at any moment, but not simultaneously. This configuration minimises the time humans and robotic agents must physically interact while guaranteeing effective resource use.
- **Cooperation:** Within the shared workspace, robots and humans have their own duties. Nonetheless, their actions are coordinated to avoid working on identical items simultaneously. This collaborative method maximises workflow effectiveness without needing face-to-face interaction.
- **Collaboration:** Within the same workstation, humans and robots collaborate in real-time on everyday activities. This cooperative arrangement promotes active collaboration by enabling both sides to work simultaneously to finish an assignment or task.

Figure 1 depicts these five modalities, illustrating the diverse ways humans and robots collaborate to achieve common goals.

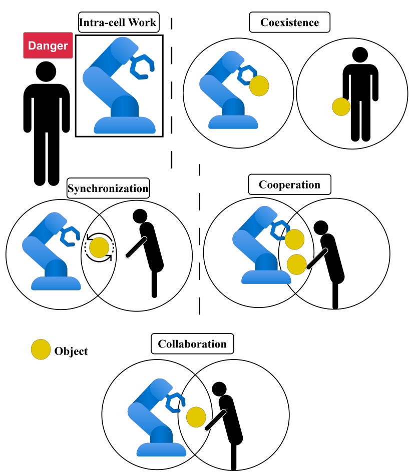

Figure 1: Modalities of Human-Robot Interaction

In healthcare, HRC frequently relies on the cognitive skills of humans to improve machine performance, particularly in carrying out repetitive or physically demanding tasks [9]. Examples include feeding disabled individuals, administering medication, and meal preparation. These activities can significantly drain the time and energy of healthcare professionals, leading to decreased efficiency and potentially compromising patient care quality. HRC facilitates delegating physically demanding tasks from human workers to robots, leading to increased overall performance through better communication channels [10]. These communication channels can have different meanings. A common goal that is understandable from both human and robot perspectives is essential to clarify this aspect. Human-to-human interaction typically involves verbal communication in the same language. Similarly, human-robot collaboration can be achieved through natural language processing or an interface to facilitate communication. Mutual interactions between humans and robots are crucial for completing tasks within collaborative systems [11]. It is essential to engage healthcare professionals and prospective patients from the outset when considering the integration of a robot into a healthcare system [12]. Finally, a robot's autonomy level is essential for determining the extent to which it can operate independently or require human supervision and intervention. Figure 2 depicts the levels of independence a robot should have in healthcare.

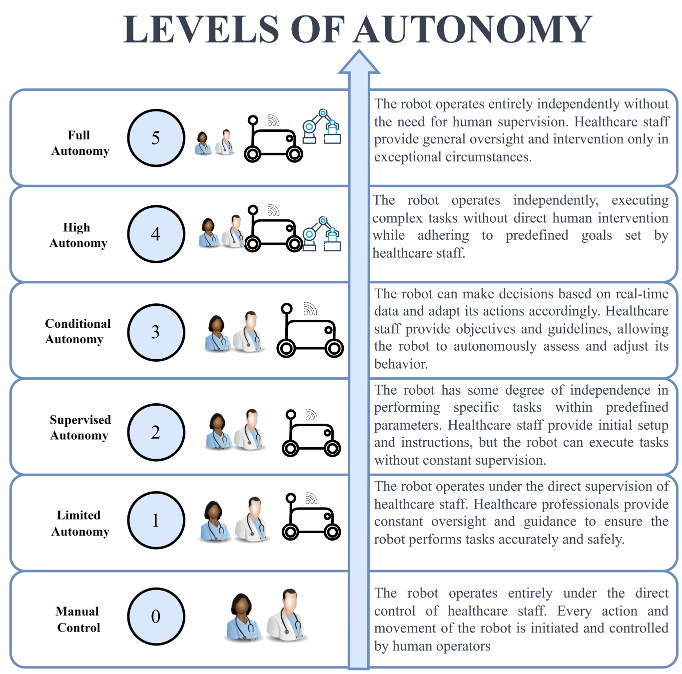

Figure 2: Levels of robot autonomy in healthcare.

III. Robotics applications in healthcare

Robotics technology has made significant strides in revolutionising various aspects of healthcare, offering innovative solutions to enhance patient care, streamline surgical procedures, aid in rehabilitation, and optimise hospital operations. Recently, healthcare professionals have heightened their focus on delivering enhanced patient treatment. In this regard, robotics is crucial in assisting these individuals, significantly improving patients' health outcomes [13]. Robotics and Artificial Intelligence (AI) can combine, with robotics facilitating interaction between doctors and patients, while AI assists in diagnosis and treatment [14]. This section explores the major types of robots present in healthcare, emphasising the collaboration between humans and robots to advance healthcare outcomes. Figure 3 presents a selection of five robotics applications within the healthcare sector highlighted in this research.

A. Patient Care and Monitoring

Regarding patient care and monitoring, robots serve as invaluable assistants, providing round-the-clock support and

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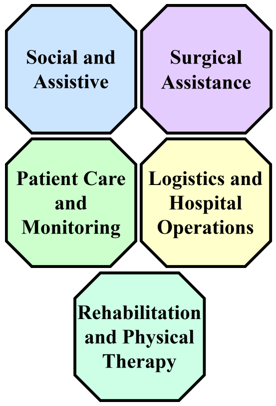

Figure 3: Robotics applications in healthcare

assistance to patients and healthcare professionals. They are commonly referred to by names such as Service Robots, Mobile Tele-presence Robots (MTR), and Tele-health Robots. They are designed for domestic duties, mobility, and health and safety monitoring [15]. These robots can address the disparity in healthcare accessibility, particularly for older adults and individuals residing in distant or underserved regions [16]. Due to the variety of telepresence robots available in this domain, one example is the Double 3 robot [17]. These robots, equipped with cameras, microphones, and screens, allow remote medical professionals to interact with patients, conduct consultations, and monitor vital signs from a distance.

B. Surgical Assistance

Surgical Robotic systems have transformed the landscape of surgical procedures, offering precision, agility, and efficiency beyond human capabilities. Robotic surgery has undeniably altered surgical intervention and practice [18]. This enables doctors to conduct a wide range of intricate procedures with greater accuracy, flexibility, and mastery compared to traditional methods [19]. Robotic surgical systems, like the Da Vinci Surgical System [20], are among the most well-known examples. These systems employ robotic arms controlled by surgeons to execute minimally invasive surgeries with greater precision, reducing patient trauma, facilitating shorter recovery times, and improving surgical outcomes. Additionally, they showcase a significant aspect of HRC, where the surgeon's skill and expertise are complemented by the precision and agility of the robotic arms, working together to achieve optimal surgical results.

C. Rehabilitation and Physical Therapy

Robots are crucial in aiding patients' recovery and regaining mobility in rehabilitation and physical therapy settings. The person with a disability undergoing treatment and the therapist facilitating and supervising the contact with the robot are the two primary users of therapy robots that operate concurrently [21]. The robot needs the capability to perceive its environment, allowing it to understand and consistently update its awareness of the current state of its surroundings [22]. For example, Exoskeleton RoboCT [23] is used in this context to support limbs and facilitate repetitive movements to strengthen muscles and improve coordination. These robots offer personalised rehabilitation programs tailored to individual patient needs, accelerating recovery and restoring independence.

D. Logistics and Hospital Operations

Efficient logistics and operations play a pivotal role in the seamless functioning of healthcare facilities, demanding considerable time and effort [24]. Hospitals increasingly turn to robotic solutions, such as Autonomous Delivery Robots and Autonomous Mobile Robots (AMRs), to address these challenges. Moxi [25] is a standout example. These robots autonomously navigate hospital corridors, optimising resource allocation, reducing manual labour, and ensuring timely delivery of essential items, thus enhancing overall operational efficiency. Furthermore, through collaboration with human personnel, these robots increase staff productivity while alleviating physical strain, enabling healthcare professionals to dedicate more attention to patient care [26].

E. Socially and Assistive Robots

Socially Assistive Robotics (SAR) is transforming our interaction with technology, offering personalised assistance to individuals and streamlining healthcare services. SAR holds excellent promise across various mental healthcare applications, providing companionship and therapeutic engagement. For instance, the integration of the Pepper robot by Aldebaran [27] with psychologists showcases its potential [28]. One key advantage of SAR lies in the human tendency to attribute human-like traits to mobile entities, which sets it apart from conventional computer apps or smartphone health applications. As SAR progresses, it continues to revolutionise the field of psychology by leveraging AI to anticipate individual needs. This advancement is complemented by the expertise of mental health professionals, including doctors and therapists, who contribute their specialised knowledge and skills. The collaboration between technology and human insight fosters an integrated approach, maximising mental healthcare outcomes.

IV. Cutting-Edge technologies in Human-Robot Collaboration for healthcare

In recent years, notable advancements in machine learning (ML) algorithms and intelligent sensor technologies have driven a significant convergence of robotics and AI fields. These developments have improved robot performance and changed the nature of Human-Robot collaboration, opening up various possibilities for improving productivity, safety, and efficiency across multiple domains. This section outlines the technologies employed in robotics within the healthcare industry.

A. Pioneering Sensor Innovations

The Internet of Things (IoT) and intelligent sensors enable continuous monitoring of patients' health, aiding doctors in delivering tailored treatments. As stated in [29], a transformation

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is occurring in the medical field due to IoT benefits. For example, in [30], a robot was developed to monitor patients' vitals and deliver essential items, supporting healthcare operations. These smart devices can be integrated into robotic systems to increase the potential for HRC in healthcare and help monitor the health status of patients in real time, providing invaluable support to medical personnel. For example, a robot embedded with IMU sensors can assist in patient rehabilitation exercises by precisely tracking movements and providing real-time feedback on posture and technique.

B. Digital Twin

Digital Twin (DT) is a digital model of the physical system designed to synchronise with the real-world process it mirrors, typically replicating its functions in real-time [31]. The potential for DT technology to revolutionise several industries, including healthcare, has lately surfaced. A virtual representation is challenging to depict since healthcare is a complex ecosystem with many different specialities [32]. Integrating DT technology and robotics in healthcare is crucial for patient monitoring. Through advanced sensors and IoT, virtual patient replicas are created to collect vital data. Robots connected to these replicas gather real-time patient information, including vital signs and movements. Human experts collaborate with these robots to refine the DT, ensuring accuracy. This collaborative approach optimises monitoring strategies, providing personalised care and enhancing outcomes. DT models can evaluate therapy success and enable early disease identification by gathering patient data constantly [33]. Moreover, rehabilitation is another area in which DT finds application. For instance, it supported an experimental platform training healthcare professionals in upper limb rehabilitation using robotic equipment [34].

C. Immersive Technologies

Immersive technology is the process of merging virtual and real-world elements such that the user may interact with the combined world intuitively [35]. Its impact in many domains, including programming, learning, and training, significantly affects HRC in the medical profession. Key immersive technologies include Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). VR immerses users entirely in virtual environments, whereas AR improves the real world by superimposing digital elements. Conversely, MR seamlessly integrates virtual and real-world interactions, allowing users to navigate and interact within this hybrid environment.

For instance, in [36], medical professionals and nurses are learning how to manipulate robotic arms through VR to operate on patients with Colorectal and Gynecological Cancer. By seamlessly integrating holographic information, AR empowers surgeons to adjust the robot's dynamically trajectory, enhancing precision and oversight during surgical procedures [37]. Furthermore, MR facilitates remote robot operation by healthcare workers, significantly minimising infection risks during patient care and sample collection [38]. Although immersive technology is still in its infancy, it shows promise to increase future HRC by enhancing communication, teamwork skills, and interface capabilities, particularly in the healthcare industry.

D. Artificial Intelligence

Artificial Intelligence (AI) describes how computer systems mimic human intellectual functions, including language comprehension, learning, reasoning, and problem-solving. According to Wang et al., [39], AI denotes the intelligence manifested by machines, which is achieved through mathematical modelling. It presents an additional avenue for creativity and transformation in healthcare delivery [40]. Recently, there has been a significant surge in the advancement of this technology across all sectors. Natural Language Processing (NLP), machine learning (supervised, unsupervised, and reinforcement learning), machine vision, and other sub-fields are becoming more and more a part of AI [41].

AI's role in Human-Robot Collaboration (HRC) in healthcare involves enabling seamless interaction and communication. AI-powered natural language processing (NLP) allows robots to understand and respond to verbal commands, enhancing efficiency in medical record retrieval, inventory management, and patient communication. This allows human caregivers to focus on more complex care aspects. The most recent innovation from OpenAI's ChatGPT, which has rapidly gained immense popularity, is among the most sought-after generative AI tools [42]. It enables robots to generate human-like responses, facilitating smoother communication and interaction. AI's ongoing development and use in HRC can transform healthcare delivery, enhancing patient experiences with safer, more intelligent, and more efficient care.

V. Challenges and Emerging Trends

While the integration of Human-Robot Collaboration (HRC) systems aims to enhance patient care by combining the expertise of healthcare professionals and robots, understanding HRC dynamics is imperative. Through a graphical depiction, Figure 4 illustrates the interconnections of various aspects crucial for efficient collaboration between care workers and robots. Notably, our investigation underscores the significance of communication in fostering seamless interactions. Moreover, trust is a pivotal component in HRC, as determined in prior studies [43, 44]. The graph underscores the importance of trust, workload distribution, feedback mechanisms, and patient safety in enhancing collaboration efficiency and reliability. This analysis visualises these interconnected components, providing insights into the complexities of HRC in healthcare and identifying avenues for future research and development in this domain.

Healthcare is a multidisciplinary sector where emerging innovations in HRC must be carefully considered. These advancements include utilising AI to make better decisions, developing user interfaces to facilitate communication, and addressing ethical issues like privacy and trust. To effectively use HRC and tackle new challenges, we need interdisciplinary cooperation and ongoing communication to manage these

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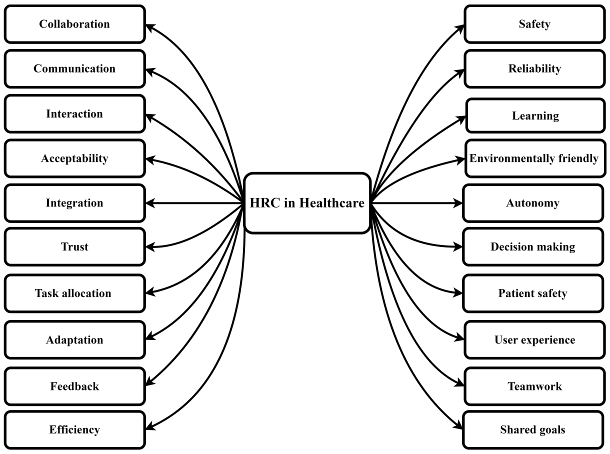

Figure 4: Dynamics interactions in Human-Robot Collaboration: A graphical representation

advancements properly. The future of HRC in healthcare settings recognises the need for a creative way to incorporate robotics into the hospital infrastructure smoothly. This solution should fulfil four critical requirements.

*1) **Enhanced Human-Robot Collaboration**:* Future developments will prioritise the smooth integration of robots into healthcare environments, guaranteeing they serve as indispensable aides and companions rather than replacing human caregivers. Maximising user experience and promoting trust between patients and robots call for further improvement in HRC mechanisms and prioritising human aspects and usability design principles.

*2) **Enhancing Robot Cognitive and Physical Abilities**:* Advancements in cognitive AI technology will enhance robots' cognitive abilities, enabling them to perform complex tasks more efficiently and adaptively. Progress in hardware technology will drive the development of physical robots capable of navigating diverse healthcare settings with unprecedented precision.

*3) **Ethical Considerations and Public Perception**:* The increasing integration of robots into healthcare operations raises important ethical and societal issues that must be addressed. Regulations and policies must ensure that robotic technology is applied ethically and protects patient autonomy, privacy, and dignity. Encouraging public participation and discourse will build community trust and acceptance of healthcare robots.

*4) **Securing Long-Term Sustainability and Resilience**:* Assuring robots' sustainability and long-term viability is essential to their development and integration into healthcare. This necessitates a multimodal approach combining regular maintenance and upkeep with strategic planning for long-term adaptation and growth of robotic systems. Proactive measures, such as regular support and upgrades, are also required to keep automated technology operating at its best and following healthcare delivery standards and practices. By prioritising robotics technology's long-term sustainability and durability, healthcare practitioners may reduce the risks associated with technological obsolescence or inefficiency while improving patient care results.

VI. Conclusion

This paper has provided a high-level review of Human-Robot Collaboration (HRC) within the healthcare sector, focusing on recent advancements, innovative technologies, and the practical implications of deploying intelligent robots in healthcare environments. Our study highlighted the potential of HRC to address critical challenges in modern healthcare, such as staffing shortages and the increasing demand for elderly care. We have identified crucial technological advancements, including pioneering sensor innovations, digital twin technology, immersive technologies, and artificial intelligence, that are driving the progress of HRC in healthcare. Additionally, we also discussed the challenges related to safety, ethical considerations, and the integration of robots into existing healthcare infrastructures.

Our findings suggest that while significant progress has been made, there are still considerable hurdles to overcome. Future research should focus on enhancing robots' cognitive and physical capabilities, ensuring ethical deployment, and fostering societal acceptance. By addressing these challenges and leveraging multidisciplinary collaboration, we can pave the way for a future where intelligent robots enhance the quality and efficiency of healthcare delivery. This paper aims to contribute to the ongoing discourse on HRC in healthcare by providing a comprehensive review and identifying avenues for future innovation and research.

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