Human-Robot Collaboration in Healthcare: A Comprehensive Review of Key Components, Applications, and Future Research

Mohamed Adlan Ait Ameur, Erfu Yang , *Senior Member, IEEE, Yin-Ping Zhang*

***Abstract*—Human-Robot Collaboration (HRC) is an emerging paradigm in healthcare that leverages robotic systems to improve patient care, assist medical professionals, and optimize clinical workflows. As healthcare demands increase due to aging populations and resource limitations, HRC offers a promising solution by combining robotic precision with caregivers' adaptability. This review provides a comprehensive analysis of HRC in healthcare, categorizing its key influencing factors into three components: (1) Healthcare Professional-Oriented, focusing on task allocation, communication, teamwork, and trust; (2) Patient-Centric, emphasizing patient safety, acceptability, interaction, and feedback; and (3) System-Critical, addressing system autonomy, adaptability, integration, and safety in medical environments. The review explores recent advancements in enabling technologies, including sensor developments, immersive interfaces, digital twin modeling, and artificial intelligence (AI), which drive more efficient and adaptive HRC. Despite these innovations, challenges such as ethical concerns, interoperability, and cost-related barriers remain obstacles to widespread implementation. Future research should focus on developing robust ethical frameworks, enhancing safety and reliability, improving interoperability, and fostering patient and caregiver acceptance through interdisciplinary collaboration.**

***Index Terms*—Human-Robot Collaboration, Healthcare robots, Patient care, Assistive robots, Collaborative robotics**

I. Introduction

THE advent of Healthcare 4.0 marks a paradigm shift towards more interconnected, efficient, and patient-centered healthcare systems powered by digital technology and automation advancements. This transformation disrupts the value chain, influencing medical production, hospital care, logistics, healthy living, and associated financial and social systems [1]. This evolution in healthcare is characterized by integrating the Internet of Things (IoT), artificial intelligence (AI), big data analytics, and robotics, creating a highly dynamic environment where technology and healthcare professional expertise converge to optimize patient outcomes and streamline operations.

Manuscript received March, 2025;
Mohamed Adlan Ait Ameur and Erfu Yang are with the Robotics and Autonomous Systems Group in the Department of Design, Manufacturing and Engineering Management, University of Strathclyde, Glasgow G1 1XJ, United Kingdom. (e-mail: adlan.ait-ameur@strath.ac.uk, erfu.yang@strath.ac.uk). (Corresponding author: Erfu Yang.)
Yin-Ping Zhang is with the Faculty of Nursing, Xi'an Jiaotong University, Health Science Center, No.76, West Yanta Road, Xi'an, Shaanxi, 710061, P.R. China. (e-mail:cathyzh@mail.xjtu.edu.cn).

As healthcare systems worldwide grapple with increasing demands due to aging populations and chronic disease prevalence, the need for scalable, sustainable, and efficient healthcare solutions becomes more acute. Healthcare systems globally encounter challenges, including limited accessibility, escalating costs, resource inefficiencies, and an aging population [2]. In addition, the worldwide society faces substantial socioeconomic issues due to the increasing age of the population, progressively stressing the sustainability of healthcare systems [3]. To directly address these growing pressures, Human-Robot Collaboration (HRC) emerges as a critical solution by complementing clinical practitioners' expertise in patient care, alleviating workload burdens, and enhancing the scalability of healthcare delivery. Robotics in Healthcare 4.0 enhances operational efficiency while expanding the precision and accessibility of medical care. Robots can assist healthcare professionals with diagnostics, surgeries, and rehabilitation [4]. The primary goal of healthcare robots is to improve care delivery, boost patient outcomes, speed up recovery, reduce pain, offer companionship, and provide emotional support while educating patients [5]. Integrating robotic systems in healthcare, direct patient care, and support services is critical for successful adoption and long-term viability.

Human-robot interaction (HRI) is about how humans and robots engage, communicate, and work together, including the design of robotic behaviors to facilitate these interactions [6]. Human-robot collaboration (HRC) refers to direct interactions between humans and robots in a shared environment, where both work cooperatively to achieve a common goal [7], [8]. HRI and HRC are inherently interconnected. HRI serves as the basis for enabling communication and mutual understanding between humans and robots, while HRC leverages this interaction to facilitate practical cooperation in shared tasks. HRC is crucial in integrating robotics into healthcare by combining human adaptability with robotic precision to enhance workflows [9].

Collaboration between humans and robots within medical environments is essential to optimize patient outcomes. Collaborations between humans and robots can encompass multiple aspects and are often described using various terms in the literature. Although the term "human-robot collaboration" might not be explicitly used in some papers, the concept is frequently conveyed through expressions such as "assist", "work alongside", "collaborate with", "team up with", "cooperate",

This is a peer-reviewed, accepted manuscript of the following paper: Ameur, M. A. A., Yang, E., & Zhang, Y.-P. (2026). Human-robot collaboration in healthcare: a comprehensive review of key components, applications, and future research. IEEE Transactions on Medical Robotics and Bionics. Advance online publication. https://doi.org/10.1109/tmrb.2026.3654137

or "augment". These alternative phrases highlight the diverse ways robots and humans interact and cooperate, emphasizing the supportive and complementary roles that robotic systems can play in enhancing human capabilities across different tasks and industries.

Recent surveys and literature reviews [10]–[17] in the field of robotics in healthcare, including HRC, have provided comprehensive overviews and insights into various aspects of this rapidly evolving field. Although these reviews have extensively covered the technological, social, and ethical aspects of robotics in healthcare, there is a pressing need for more focus on the integrative approach encompassing healthcare professional-oriented, patient-centric, and system-critical factors. Specifically, the balance between caregiver needs and technical capabilities, the alignment of robotic systems with clinical objectives, and the optimization of collaborative processes still need to be explored.

To comprehensively understand the current state and scope of Human-robot collaboration in healthcare, a comprehensive literature search was conducted up to 2024. Reputable academic databases were utilized, including Google Scholar, PubMed, Web of Science, Scopus, IEEE Xplore, and CrossRef. Relevant research articles, reviews, and conference papers were identified using keywords and phrases such as "human-robot collaboration", "human-robot interaction", "healthcare robots", "human-robot collaboration in healthcare", and "assistive robotics in healthcare". Variations of these terms were considered to ensure comprehensive coverage of the literature. Articles were selected based on their focus on integrating robots into healthcare environments, particularly in the context of human-robot collaboration. A systematic data extraction process was employed, capturing details such as publication date, study objectives, methodologies, key findings, and discussions on innovation and challenges. The collected data were then synthesized to present a comprehensive analysis of advancements in human-robot collaboration in healthcare, the challenges encountered, and prospects in the field.

This review article is structured as follows: Section II explores the conceptual foundations of HRC in healthcare. Section III examines its applications, while Section IV discusses recent technological advancements that enhance HRC capabilities. Section V presents key findings and outlines future research directions to address existing challenges and gaps. Finally, Section VI concludes the article by evaluating the potential of HRC to address current and emerging healthcare challenges, providing insights from the literature on its essential aspects.

II. Conceptual Foundations of Human-Robot Collaboration in Healthcare

Healthcare systems around the world are under increasing pressure due to aging populations, a rise in chronic diseases, and a shortage of healthcare professionals. Like many healthcare systems worldwide, the UK is no exception, with GPs reporting higher levels of stress and dissatisfaction compared to their international counterparts. The growing workload, patient demand, and coordination challenges contribute to this strain, making retention of healthcare professionals as critical as recruitment [18]. These challenges require innovative solutions to improve the quality and efficiency of healthcare delivery. Technological advancements in automation and artificial intelligence have paved the way for new approaches to patient care. Among these innovations, integrating robotics into healthcare has emerged as a promising strategy to alleviate workforce shortages while enhancing safety, efficiency, and personalized care [19]. There has been a surge in publications on the use of robots in healthcare [20], and robots at various stages of development are being introduced into hospitals, care facilities, and homes [21]. Consequently, human-robot collaboration has become increasingly important in improving healthcare services. By working alongside healthcare professionals, robots can assist in tasks ranging from surgery to rehabilitation, addressing critical needs such as precision in medical procedures and personalized patient care. This collaboration offers new possibilities for enhancing patient outcomes and redefining traditional healthcare practices.

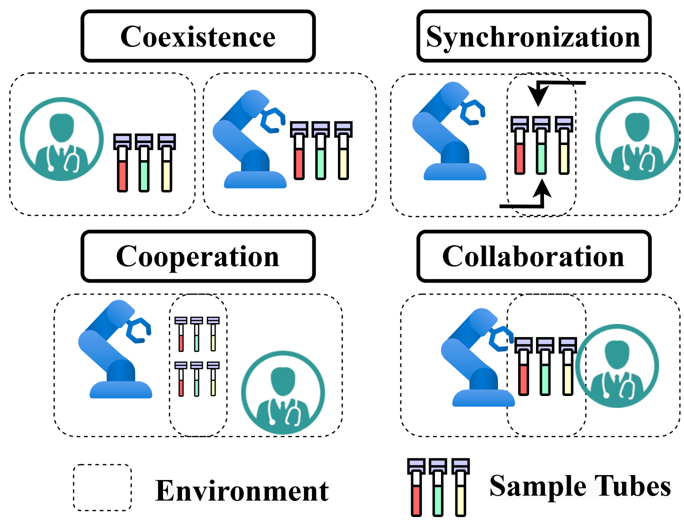

Fig. 1. Levels of interaction in HRI.

Understanding the different levels of interaction between humans and robots in healthcare settings is essential. As illustrated in Figure. 1, these interactions can be categorized into four distinct levels: coexistence, synchronization, cooperation, and collaboration [22]. Each level represents a progressively deeper integration of human and robot functions, moving from essential task sharing to fully collaborative efforts, where human and robotic systems work together to achieve common goals.

- **Coexistence:** At this level, humans and robots operate in the same environment but maintain separate workspaces. The robot performs its tasks independently without sharing a physical space with human workers. A notable example is a private outpatient pharmacy in Saudi Arabia that implemented a robotic dispensing system to handle medication preparation in a secured area while pharmacists focused on patient counseling. This setup led to a 53% reduction in wait times, a 33% increase

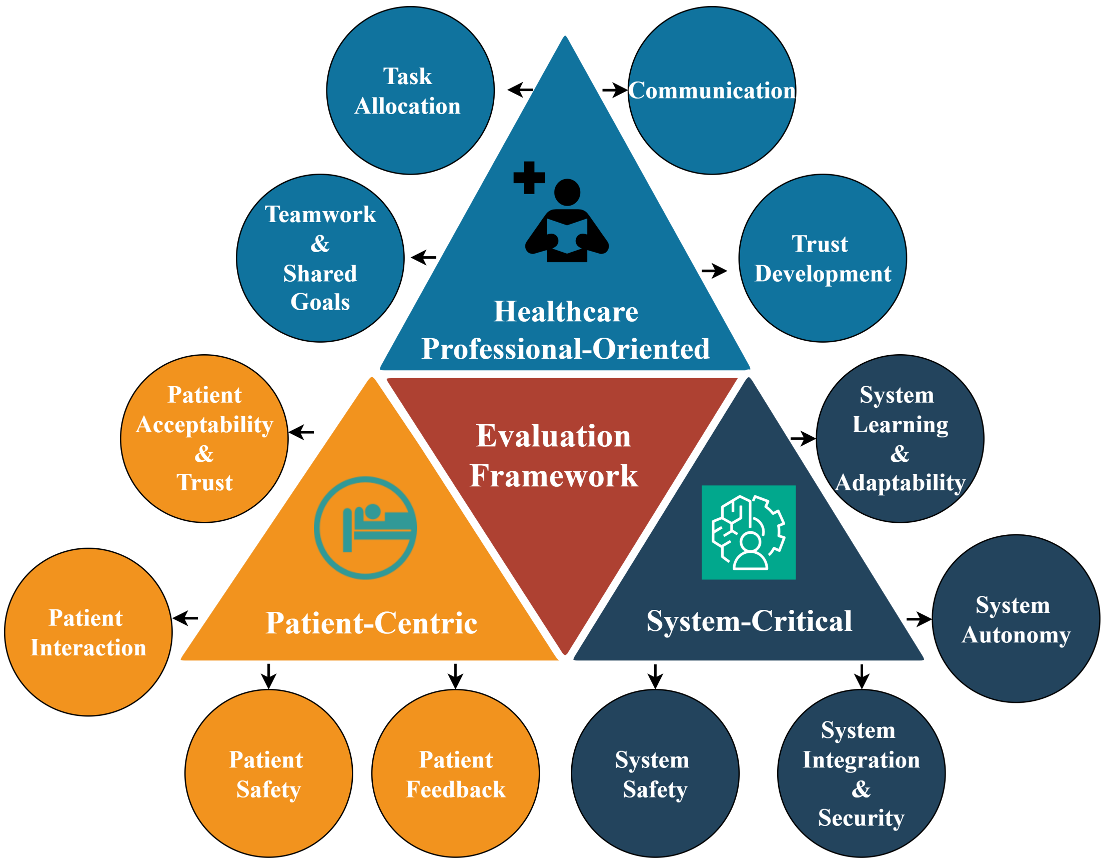

Fig. 2. An evaluation framework for healthcare professional-oriented, patient-centric, and system-critical components in Human-Robot Collaboration.

in pharmacist productivity, and zero dispensing errors, demonstrating effective parallel operation without physical interaction [23].

- **Synchronize:** In this type of interaction, humans and robots share the same workspace but not simultaneously. Their tasks are sequentially organized so that the other is not present when one is active in the shared space. A real-world example in healthcare is using UV-C disinfection robots in hospital outpatient settings. After hospital staff manually clean a room following standard operating procedures (SOP), the area is cleared and sealed. The disinfection robot is then remotely activated to operate autonomously in the unoccupied space, emitting UV-C light for 20–25 minutes [24]. This sequential workflow ensures that human and robot activities do not overlap, enhancing safety and efficiency.
- **Cooperation:** At the cooperation level, humans and robots work in the same workspace simultaneously but on separate tasks. They operate side-by-side, each focusing on their responsibilities without directly interfering with one another. For instance, mobile service robots were deployed in hospital logistics to support kitchen staff by automating courier tasks. While both worked in parallel, ethnographic observations revealed that cooperation involved navigating dynamic workflows and adapting to evolving practices, highlighting the need to consider robots as organizational change agents [25].
- **Collaboration:** Collaboration is the most integrated level of interaction, where humans and robots work together in real time on the same task or component. This requires communication and coordination between the human and the robot. For example, a robotic system assisting nurses in patient handling reduced maximum force exertion by 51%, trunk torsion by 87%, and spine muscle activity by 55%. These reductions highlight the effectiveness of robotic collaboration in reducing injury risk and physical strain, promoting safer working conditions for healthcare workers [26].

Collaboration in healthcare systems involves staff within the same facility, between multiple institutions within a network, and with external organizations and systems [27], while also emphasizing the importance of integrating robots designed to complement care workers' capabilities in these collaborative environments. In nursing, for example, robots can assist by monitoring patients, administering medications, and providing mobility support. These roles allow healthcare providers to focus on more complex, patient-centered aspects of care. Robots can improve the quality of healthcare delivery and patient outcomes by serving as valuable tools that augment healthcare professionals expertise. For robots to be practical, they should be developed as collaborative tools, focusing on tasks where they excel without attempting to replace human roles rooted in empathy and personal care [28], [29]. Achieving collaboration requires a structured evaluation of the core components that facilitate successful interactions between healthcare professionals, patients, and robotic systems. Figure 2 demonstrates the impact of healthcare professional-oriented, patient-centric, and system-critical factors, which create a foundational basis for the deployment of robots in clinical settings.

A. Healthcare Professional-Oriented Factors

Healthcare professional-oriented factors enable successful collaboration between clinical staff and robotic systems. These factors emphasize the collaborative processes and interactions between healthcare professionals such as doctors, nurses, therapists, and robots, ensuring that technology complements and enhances their roles without disrupting workflows. Key healthcare professional-oriented factors include:

- **Communication:** Effective communication capabilities are crucial for healthcare robots, as they often interact with vulnerable individuals, including the aging society, patients with health conditions, or those recovering from injuries [30]. Robots must accurately interpret inputs from healthcare staff, whether verbal commands, gestures, or other non-verbal cues, to provide timely and relevant responses. This ensures that robotic technologies support clinical decision-making and patient care workflows, fostering smooth, responsive interactions that align with healthcare demands.
- **Task Allocation:** The allocation of tasks optimizes the complementary strengths of healthcare professionals and robotic systems. Robots are assigned tasks requiring high precision, repetitive actions, or exposure to potentially hazardous conditions, while healthcare staff focus on roles demanding critical thinking, empathy, and complex decision-making. This approach maximizes efficiency and enhances the quality of patient care. Robots can enhance efficiency by optimizing delivery times, thereby contributing to improved quality of care in healthcare settings [31].
- **Teamwork and Shared Goals:** Task coordination is often structured hierarchically, with a designated leader overseeing operations while other members fulfill supporting roles [32]. Teamwork between robots and caregivers improves healthcare services. This involves robots that function as collaborative partners, communicate clearly with team members, and understand team dynamics. Ensuring that robotic functions support shared goals such as improving patient outcomes, increasing access to care, and optimizing operational efficiency strengthens the partnership between care workers and robots.
- **Trust Development:** In healthcare, cultivating trust between humans and robots is essential and should approach the level of trust typically reserved for human caregivers, such as the bond between patients and healthcare professionals [33]. However, ambiguity in the role, especially in critical areas such as surgery or diagnostics, can undermine this trust, mainly when robotic errors occur. Building and maintaining trust relies on the robot's ability to perform reliably, transparently, and predictably in high-stakes settings. To support this, structured training, clearly defined roles, and robust error mitigation protocols are vital to ensure that robots are perceived as dependable partners in patient care.

B. Patient-Centric Factors

These criteria assess robotic systems from the patients' perspective, focusing on their experience and acceptance:

- **Patient Interaction:** Patient-robot interaction is crucial for fostering trust, comfort, and adherence to treatment, particularly in assistive and rehabilitative settings. Interaction strategies should be adapted based on demographic aspects, including age, cognitive ability, and cultural background, as these elements significantly influence patient preferences regarding robot behavior, social cues, and communication styles. Robots designed with social cues or anthropomorphic features can enhance engagement, reduce anxiety, and create a more intuitive experience.
- **Patient Safety:** Patient safety, a concept derived from the healthcare industry, refers to preventing avoidable harm and adverse incidents [34]. Ensuring patient safety involves preventing physical harm, protecting patient privacy, and maintaining the integrity of care processes. Robots must be designed to avoid accidents, such as unintentional contact or exposure to contaminants. Compliance with regulatory standards, such as those set by the European Medicines Agency (EMA), the U.S. Food and Drug Administration (FDA), and other international bodies, is essential for certifying the safety and efficacy of robotic systems used in clinical practice. These agencies establish guidelines that require testing and validation to ensure that healthcare robots operate safely and support quality care, protecting patient well-being worldwide.
- **Patient Acceptability and Trust:** Assessing the degree to which patients feel safe and comfortable interacting with robotic systems, including acceptance influenced by usability and personal preferences. Patient trust in HRC is a vital aspect influencing the adoption and effectiveness of robotic systems in healthcare [35]. Understanding how individuals perceive robots, develop attitudes and expectations, and make interaction decisions is essential to predict acceptance in HRI [36]. Elements influencing acceptability include perceived usefulness, ease of integration into existing workflows, and cultural attitudes toward technology. Strategies to improve acceptability and trust involve participatory design approaches in which patients participate in the development process, ensuring that the technology meets their needs and expectations.
- **Patient Feedback:** Patient feedback is refining robotic systems to meet patient needs better. Although seemingly trivial for humans, a robot must ensure that it engages the correct patient, maintains sufficient engagement throughout the interaction, and receives the appropriate feedback from the patient [37]. This feedback can be collected through explicit channels, such as verbal or written comments, surveys, and structured interviews, or through implicit channels, such as data from sensors that monitor

patient behavior, physiological responses, and levels of engagement.

C. System-Critical Factors

The critical factors of the system focus on the technical, operational, and regulatory aspects of robotic systems in healthcare. These factors ensure that robotic systems are safe, reliable, and capable of meeting the high standards required in clinical environments.

- **System Safety:** System safety is the primary concern in healthcare robotics. Robots must comply with internationally recognized safety standards set by organizations such as the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC). For example, ISO 13482 [38] provides guidelines for personal care robots, while IEC 60601 [39] addresses the safety requirements for medical electrical equipment. Robot safety features include physical protections such as emergency stop buttons, software interlocks, and fail-safe mechanisms. Comprehensive risk assessments are conducted to identify and address potential hazards, ensuring safe operation in healthcare settings.
- **System Learning and Adaptability:** System learning capabilities enable robots to improve over time. Robot adaptability is the capacity of a robot to adapt to new environments with various characteristics [40]. Robots can adjust to new tasks and environments through supervised, reinforcement, and deep learning. Machine learning advances primarily assist healthcare professionals in task performance, trend analysis, and disease prediction [41]. This involves improving diagnostic algorithms based on new data or personalizing rehabilitation exercises for individual patients in healthcare. However, increased adaptability through machine learning also introduces potential unpredictability, posing challenges to patient safety. The dynamic nature of learning algorithms requires careful management, extensive validation, and rigorous safety protocols to ensure adaptive behaviors do not compromise patient protection. Balancing flexibility in adaptation with strict safety standards remains a critical challenge in deploying adaptive robotic systems in healthcare environments.
- **System Integration and Security:** Seamless integration ensures that robotic systems operate reliably within the established healthcare setting. This requires technical compatibility with existing systems and routines, enabling healthcare staff to use robotic support without disrupting care processes. Regardless of functionality, a robot will not be widely adopted without robust mechanisms to ensure privacy and security [42]. Ethics involves evaluating actions by carefully weighing their potential harms and benefits [43]. Patient consent and data security are vital ethical considerations in these integration processes. Ensuring data security is particularly challenging due to the diverse regulatory frameworks across regions, such as the General Data Protection Regulation (GDPR) in Europe and the Health Insurance Portability and Accountability Act (HIPAA) in the United States, each with distinct compliance requirements. Robotic systems must, therefore, implement adaptable data governance strategies capable of addressing multiple regulatory environments, ensuring consistent compliance, robust security practices, and protecting sensitive patient information.
- **System Autonomy:** Autonomy describes a machine's capability to function independently for a certain duration without human intervention [44]. Robot autonomy is fundamentally derived from its control algorithm, dictating the ability to execute tasks independently [45]. The level of autonomy in robotic systems ranges from teleoperated devices to fully autonomous robots. In healthcare, autonomy must be carefully balanced with the need for human oversight. Autonomous robots perform environmental disinfection, patient transport, or routine monitoring, operating under predefined parameters while allowing human intervention when necessary.

Understanding and refining the factors enabling collaboration between healthcare professionals and robots are crucial for successfully deploying robotic systems in healthcare settings. These conditions are organized into three complementary components: Healthcare Professional-Oriented, Patient-Centric, and System-Critical, each comprising specific factors that shape the quality and effectiveness of human-robot collaboration.

III. Applications of Human-robot collaboration in healthcare

Building upon the conceptual foundations of HRC discussed earlier, we now explore how these components are implemented across various healthcare applications. By examining real-world examples, we illustrate how healthcare professionals-oriented, patient-centric, and system-critical factors are integrated to improve patient care and address diverse healthcare challenges. Figure 3 highlights key areas of robotic application in healthcare, classified by different types of impairments, and emphasizes the multifaceted role of robots in meeting diverse patient needs.

A. Social Assistive Robotics

a) Healthcare Professional–Oriented Perspective: Social and assistive robots often collaborate with healthcare providers to enhance operational workflows and reduce clinical staff workloads. Automating repetitive tasks and providing real-time patient data enables these robots to support carers in focusing on advanced decision-making and direct patient care. For instance, a socially assistive robot integrated into a retirement home environment helped caregivers by announcing events, reducing their overall workload, and enhancing social interactions among residents [46]. Linking these robots with other medical equipment can also streamline healthcare processes, marking efficient service delivery [47].

b) Patient-Centric Perspective: Socially Assistive Robots (SARs) such as Pepper provide emotional support, cognitive exercises, and companionship, which are beneficial for addressing emotional and mental health concerns. Using

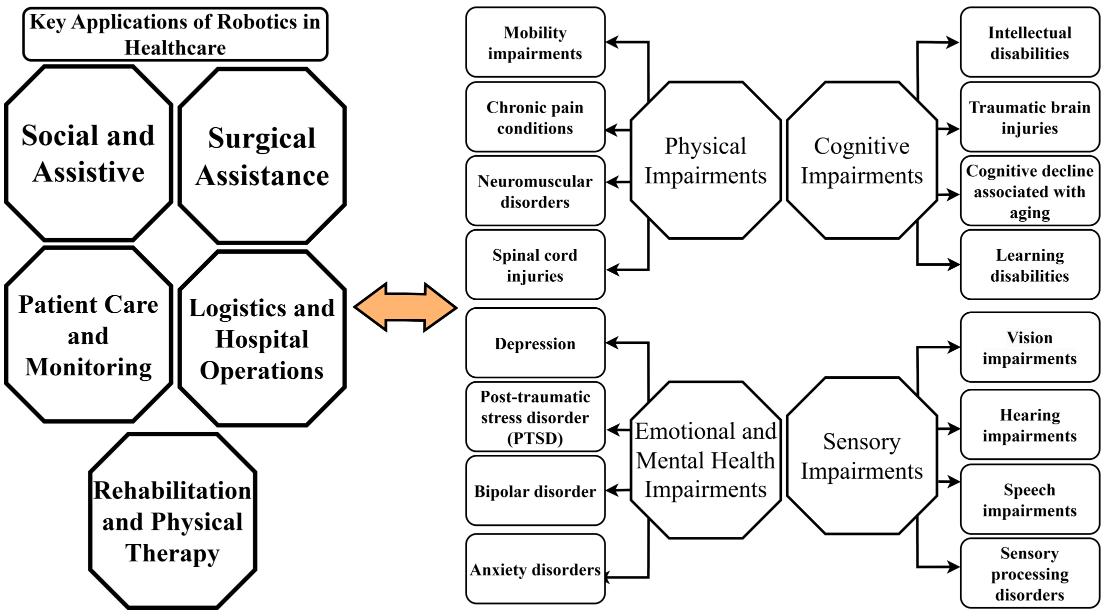

Fig. 3. Key applications of robotics in healthcare and their role in addressing various impairments

AI for emotional recognition and personalized interaction, these systems adapt to individual patient needs, building trust through consistent, non-threatening encounters [48]. Moreover, a conceptual framework in ASD therapy proposes the integration of real-time cognitive data analysis with expert input to support adaptive therapy management and continuous monitoring in robot-assisted interventions [49]. Another example, a meta-analysis by Lu et al. (2021) [50] pooled 3 Randomized Controlled Trials (RCTs) (214 patients) and found that a pet-type companion robot produced a moderate reduction in agitation (standardized mean difference -0.37, $p < 0.01$. Longer or more frequent robot sessions were also associated with lower depression scores in these patients. These examples highlight how adaptability and patient feedback improve acceptability and user satisfaction.

c) System-Critical Perspective: Ensuring safe navigation, reliable data exchange, and integration into clinical workflows is pivotal for social and assistive robots [19]. Adherence to stringent safety standards is particularly critical when interacting with vulnerable populations, necessitating the implementation of robust communication protocols to safeguard patient confidentiality and data integrity. Additionally, learning capabilities enable these robots to improve over time, enhancing adaptability to diverse environments and evolving healthcare needs. Involving clinicians and patients in the development and testing phases enables these systems to address usability and security concerns better, thereby meeting high system-critical requirements.

B. Surgical Assistance

a) Healthcare Professional-Oriented Perspective: Surgical robotics elevate clinical performance by combining the surgeon's expertise with the robot's precision. For instance, the robot's da Vinci surgical system leverages robotic skill to enable minimally invasive procedures, reducing manual fatigue and improving task allocation between surgeons and machines [51]. Communication and collaboration are essential, as demonstrated through the coordination between surgeons and robots via hand-guiding interfaces in spinal surgery [52] or augmented reality guidance in percutaneous nephrolithotomy (PCNL) [53]. Optimizing task distribution, such as assigning the robot to handle precise movement while the surgeon focuses on higher-level decision-making, can streamline workflows and enhance surgical outcomes [54].

b) Patient-Centric Perspective: From the patient's perspective, robotic patient surgery improves safety and overall experience by reducing invasiveness, shortening recovery times, and enhancing surgical precision. Incorporating semi-autonomous systems, such as a suction tool that adjusts dynamically in response to the surgeon's mental workload, highlights the importance of adaptability and real-time feedback in ensuring patient safety [55]. A meta-analysis of 2,660 patients showed that robotic thyroidectomy, compared to open surgery, led to longer operative time. However, it offered shorter hospital stays, less bleeding, and better cosmetic satisfaction $p < 0.05$ [56]. These outcomes underscore the role of robotic surgery platforms in reducing infection risk and improving precision through smaller incisions, aligning with patient-centric goals of trust, comfort, and faster recovery.

c) System-Critical Perspective: Surgical robotics must comply with international safety standards and incorporate fail-safe mechanisms to prevent accidents, underscoring the importance of system-critical factors such as autonomy and system integration. These platforms rely on advanced sensor data, real-time monitoring, and strict regulatory guidelines to maintain consistent, high-quality performance under different clinical conditions. Continuously learning from surgeons through interactive collaboration and data-driven feedback, these systems can refine their precision and adapt to evolving surgical techniques.

C. Patient Care and Monitoring

a) Healthcare Professional-Oriented Perspective: Robotic systems for patient care and monitoring help healthcare providers track patients' conditions remotely and streamline everyday tasks. For instance, telepresence robots enable real-time interaction with patients with chronic illnesses, allowing caregivers to monitor vitals and provide timely interventions [57]. Nursing simulations increasingly leverage telepresence robots for remote student collaboration [58], showcasing how robots can facilitate teamwork, enhance training, and support overall staff efficiency.

b) Patient-Centric Perspective: These technologies enhance accessibility to healthcare by minimizing travel requirements, particularly for individuals with mobility or sensory impairments. Interactions with telepresence robots must be intuitive and user-friendly, emphasizing high acceptability and satisfaction. In a survey study on unselected urological patients using a telepresence robot, 71% of patients expressed willingness to use the system in future visits [59]. Advanced sensing robots offer responsive and personalized support, which can be pivotal for early detection of health issues among individuals with cognitive impairments [60]. Patients trust and feedback are to refine interfaces and interaction modalities, ensuring safe, comfortable engagement that aligns with their expectations.

c) System-Critical Perspective: Privacy concerns remain critical in patient monitoring applications. Telepresence robots and related technologies must secure data transmission and protect patient confidentiality [61]. Seamless integration with healthcare networks, ensuring robust performance, enables professionals to access real-time patient data without compromising reliability or security.

D. Logistics and Hospital Operations

a) Healthcare Professional-Oriented Perspective: Robots in logistics and hospital operations can reduce the workload of clinical staff by automating vital tasks. For instance, collaborative robots (cobots) handle time-consuming duties such as delivering supplies or medications, enabling healthcare professionals to concentrate more on patient-centered care [62]. Streamlined task allocation and efficient workflow management help providers have adequate time to interact with patients and address complex care needs, improving overall healthcare delivery quality.

b) Patient-Centric Perspective: The efficient and reliable delivery of medications, meals, and other essential items through mobile service robots enhances the timeliness of healthcare services, contributing to improved patient safety and comfort [25] [63]. The reduced risk of contamination also supports maintaining a hygienic environment, thereby minimizing infection hazards. Integrating assistive robots into daily hospital routines helps preserve patient trust and overall acceptability by minimizing disruptions and allowing staff to remain focused on patient well-being.

c) System-Critical Perspective: System integration and safety are critical in robotic logistics. Robots must operate consistently in complex hospital environments, employing robust frameworks for hazard detection and avoidance [64]. For example, robotic preparation of sterile medication doses has been shown to prevent approximately 5,420 medication errors annually and generate estimated cost savings of $288,350 per year, based on simulation models using published error rates and clinical outcomes. This highlights automation's role in enhancing safety and improving hospital systems' economic efficiency [65]. Continuous learning and autonomy allow robots to adapt to dynamic conditions, maintaining efficiency even as patient volumes fluctuate. Ensuring interoperability with hospital infrastructure, such as electronic health records or scheduling systems, reduces potential disruptions and preserves patient confidentiality.

E. Rehabilitation and Physical Therapy

a) Healthcare Professional-Oriented Perspective: Robotic systems in rehabilitation assist therapists by delivering consistent, data-driven therapy sessions, thus optimizing task allocation and reducing human error. For instance, robots can collaborate with physiotherapists to provide individualized treatment plans, ensuring precise and repetitive exercises for patients with physical impairments [66]. This approach supports therapists in monitoring progress and fosters open communication and trust, as therapists rely on robotic data to tailor interventions and enhance workflow efficiency.

b) Patient-Centric Perspective: From the patient's standpoint, these robotic solutions, ranging from social robot–augmented telepresence for remote guidance [67] to wearable exoskeletons [68], can improve the rehabilitation experience. Immediate feedback and adaptive movement corrections boost engagement and motivation, key elements in successful therapy. Additionally, devices such as exoskeletons aid in restoring mobility and independence, contributing to a better quality of life [69]. Meta-analytical evidence shows that robot-mediated therapy significantly improves patients' walking independence compared to conventional treatment, with overall odds ratios (OR) ranging from 2.28 to 2.45 across different studies [70]. Ensuring patient safety through adherence to medical device regulations and maintaining a positive user experience further enhance trust and acceptability, encouraging consistent use and better outcomes.

c) System-Critical Perspective: For rehabilitation technologies to be effective at scale, they must operate safely across diverse environments. Robot sensors gather patient data to personalize exercises, while robust control algorithms adapt interventions in real time. Compliance with regulatory standards ensures that devices meet high safety benchmarks, mitigating risks such as accidental injuries.

Across these diverse applications, human-robot collaboration demonstrates its capacity to address a range of healthcare challenges by combining the expertise of clinical staff with the precision and adaptability of robotic systems. The foundational factors of communication, trust-building, task allocation, and safety appear consistently across domains from surgical assistance to patient monitoring and rehabilitation, revealing the impact of healthcare professional-oriented, patient-centric, and system-critical factors. By leveraging these factors, robots can provide mobility support for physical impairments, cognitive engagement for individuals with memory or intellectual challenges, emotional assistance in mental health, and sensory aid for those with visual or auditory deficits.

IV. Technological Advancements Facilitating Human-Robot Collaboration

Recent technological advancements have had a profound impact on the healthcare sector. These technologies enhance patient outcomes and transform healthcare service delivery by enabling robots to assist professionals in complex tasks. This section explores critical developments in sensors, immersive technologies, digital twins, and artificial intelligence, discussing their contributions to advancing HRC in healthcare and potential consequences.

A. Advancements in Sensor Technologies

Sensor technology has evolved to provide robots with enhanced perception capabilities, crucial for safe and reliable HRC in healthcare settings. Integrating advanced sensors allows robots to interact precisely and safely with humans, facilitating closer collaboration. The development of the Internet of Things (IoT)-driven sensor technology is pivotal in enabling real-time data collection and decision-making in robotics applications within healthcare [71]. For instance, IoT sensors allow robots to monitor patients' vital signs and track medication intake, thereby supporting healthcare professionals with timely and accurate data for decision-making and remote care. Despite these benefits, challenges such as sensor reliability, environmental sensitivity, and potential cybersecurity threats remain barriers to adoption in critical healthcare environments.

Moreover, the Internet of Robotic Things (IoRT) extends the capabilities of IoT by integrating robotic systems with IoT devices, enabling robots to collect and process sensor data in real-time and communicate with other medical devices [72]. This advancement enhances HRC by improving decision-making and enabling more precise patient monitoring, but latency in real-time processing and interoperability issues between different IoRT platforms remain key limitations. Advanced sensors such as haptic feedback and force sensors are critical in enhancing HRC, particularly in soft medical robotics [73]. These sensors empower robots to sense and respond intuitively to their physical environment, ensuring safer collaboration with human partners. Nevertheless, they can be prone to wear and calibration drift over time, which affects their performance in dynamic healthcare settings. High computational demands and complex calibration processes limit these sensors' availability in resource-constrained facilities. Nonetheless, continued progress in robotic sensor technology is driving safer, closer, and more adaptable human-robot interactions, substantially contributing to the effectiveness of HRC in healthcare [74].

B. Immersive Technologies

Immersive technologies, including augmented reality (AR), virtual reality (VR), and mixed reality (MR), have become integral in enhancing HRC in healthcare by providing intuitive and interactive interfaces for collaboration. In rehabilitation, integrating VR with robotic devices has made therapeutic experiences more engaging and motivating for patients [75]. By creating immersive, task-oriented, and interactive environments, VR facilitates patient recovery through physical and cognitive engagement [76]. This enhances patient outcomes and improves collaboration between therapists and robotic systems, as the immersive environment allows for better monitoring and adaptation to patient needs. However, the accessibility and affordability of high-fidelity VR systems pose challenges in resource-limited healthcare settings, and prolonged VR exposure may cause motion sickness and cognitive fatigue, potentially limiting patient compliance in long-term rehabilitation programs.

Mixed reality technologies enable intuitive HRC in tasks such as telesurgery [77]. MR provides real-time visual feedback in a three-dimensional space, allowing surgeons to control robotic systems more precisely during remote procedures. The enhanced interaction between surgeons and robots through MR technology improves surgical outcomes and demonstrates the potential for more complex collaborative tasks in healthcare. Nonetheless, MR systems demand substantial computational power and high-bandwidth connectivity, which can lead to latency problems in real-time applications. In addition, ensuring accurate and stable MR overlays remains challenging, particularly in the dynamic environment of surgical procedures.

Augmented reality has also been integrated with robotic systems to enhance precision in complex surgical tasks. For instance, AR can assist in tool placement by overlaying digital information onto the surgeon's view, improving depth perception and accuracy [78]. While this capability offers clear benefits, AR's reliability hinges on precise calibration and tracking accuracy, which lighting conditions and occlusions can undermine. Moreover, the potential for cognitive overload from excessive visual information may impede decision-making in high-stakes procedures. These immersive technologies strengthen HRC by providing more natural and intuitive interfaces, facilitating better communication and collaboration between healthcare workers and robots in healthcare settings [79]. Addressing technical limitations, user adaptation challenges, and ethical concerns related to data privacy and patient consent will be crucial for their broader adoption and long-term integration into clinical workflows.

C. Digital Twin

Digital Twin (DT) involves creating virtual replicas of physical systems that are updated in real-time, enabling enhanced monitoring, simulation, and control capabilities. In healthcare, digital twins can replicate specific patients or entire healthcare systems, providing a powerful tool for analysis and optimization [80]. Developing a DT for multi-robot surgical platforms allows real-time synchronization between physical robots and their digital counterparts [81]. This synchronization enhances HRC by enabling precise control and monitoring during surgical procedures, improving surgical outcomes. Surgeons can simulate procedures, anticipate potential problems, and adjust strategies accordingly, resulting in better collaboration with robotic systems. Integrating DT technology with IoRT-enabled robotic systems and wearable devices facilitates real-time monitoring of patient vitals, supporting healthcare decision-making through continuously updated data [82]. These advancements form a foundational element for HRC, enabling robots to assist healthcare professionals by providing timely and accurate patient information, thus improving the efficiency of collaborative healthcare tasks. However, the high computational demand and real-time data processing requirements pose challenges for large-scale implementation, particularly in settings with limited infrastructure. Additionally, ensuring the accuracy and reliability of DT models is crucial, as discrepancies between virtual simulations and physical reality could lead to unintended outcomes.

Furthermore, digital twins of robotic systems monitor and optimize real-time robotic performance, enabling predictive analysis and continuous improvement. For example, integrating digital twin-based large-area robot skin systems can improve safety in system-centered healthcare robots by enhancing real-time monitoring and decision-making [83]. Providing precise and timely information, DT technology boosts the efficiency of HRC in healthcare. Although these innovations bring substantial benefits, maintaining the long-term reliability of DT models under dynamic healthcare conditions remains an ongoing challenge.

D. Artificial Intelligence

Artificial intelligence (AI) is pivotal in advancing HRC by enabling robots to learn, adapt, and make real-time decisions. AI enhances diagnostic accuracy, assists in surgeries, and personalizes patient care, making robots more capable collaborators in healthcare environments. Large language models (LLMs) are utilized to enhance socially assistive robots (SARs) by improving natural language understanding and interaction [84]. This enhancement facilitates more natural and intuitive communication between patients and robots, improving personalized care and strengthening HRC. However, LLMs can generate unpredictable responses, raising concerns about reliability, patient trust, and ethical implications in sensitive healthcare interactions. These challenges highlight the need for transparent and explainable AI-driven communication to ensure safe and trustworthy patient-robot interactions.

Healthcare robots can engage in meaningful conversations, understand patient needs, and provide appropriate responses, enhancing the therapeutic relationship. AI technologies are increasingly embedded in developing robotic systems to optimize classification, language understanding, and image analysis [85]. Multimodal perception systems, powered by AI, enable social and assistive robots to interact reliably with humans in dynamic environments [86]. By processing data from multiple sensors, such as visual, auditory, and tactile inputs, these systems enable robots to assist in patient monitoring and rehabilitation, enhancing collaboration with healthcare professionals. Despite these advantages, AI-driven perception systems often face challenges adapting to real-world variabilities, such as diverse patient behaviors, fluctuating environments, or sensor failures. Additionally, bias in training data can compromise fairness and accuracy in AI-assisted decision-making, posing risks in clinical scenarios.

AI-enabled robots assist with monitoring, mobility, and personalized care tasks, providing more intelligent and adaptive support to patients and healthcare professionals [87]. Robots can adapt to individual patient needs through AI-driven interventions, learning from interactions to improve over time. This adaptability is crucial for successful HRC, allowing robots to function in complex and changing healthcare environments. Reinforcement learning (RL), a subset of AI, enhances healthcare and robotics applications [88]. It can be used to support improved decision-making in physical HRC tasks such as grasping and manipulation. These advancements directly impact healthcare operations by enhancing robotic assistance during surgeries or patient care. However, training RL models requires extensive computational resources, and their decision-making process is often difficult to interpret, making it challenging to ensure transparency and accountability in healthcare settings.

Despite its transformative potential, AI faces notable limitations that can hinder its safe deployment in healthcare. One primary concern is algorithmic bias, often stemming from non-representative training data, which can lead to disparities in care for underrepresented groups. AI algorithms with inherent bias may fail to deliver appropriate care to specific patient populations, leading to serious negative consequences, including increased risk of harm [89]. Additionally, AI systems may struggle to generalize to unfamiliar scenarios or rare conditions, posing risks to patient safety. These challenges highlight the importance of diverse datasets, ongoing model validation, and domain adaptation to ensure that AI-powered robotic systems can support equitable and reliable human-robot collaboration across varied and evolving clinical environments.

With the continued advancement of AI-driven robotic technologies, there is an anticipation of increased deployment of autonomous robotic assistants collaborating with surgeons [75]. These robotic assistants are expected to augment surgeons' abilities and broaden the spectrum of operations available in the operating room, thereby enhancing surgical outcomes and patient care. AI technologies strengthen HRC by enabling robots to communicate effectively, adapt to dynamic environments, and assist in complex decision-making processes. This transformation leads to more efficient healthcare delivery, improved patient outcomes, and a strengthened partnership between humans and robots in healthcare settings. Nevertheless, ensuring regulatory compliance, addressing liability concerns in AI-driven errors, and establishing standardized protocols for AI-integrated robotic systems remain critical challenges before widespread adoption.

V. Key Findings and Future Research Directions

The study underscores the importance of communication channels and intuitive interfaces, which ensure effective interaction between healthcare professionals and robotic systems. Prior studies emphasize that understanding the appropriate timing for communication is essential for overcoming interaction barriers and ensuring smooth coordination between robots and caregivers [90]. Practical communication skills are crucial to healthcare robots, particularly when interacting with vulnerable users who may be elderly, ill, or injured [30]. Technologies such as speech recognition, gesture interpretation, and haptic feedback enhance the naturalness of HRC, thereby improving patient experience.

Trust is a critical factor influencing the adoption of robotic systems in healthcare. Integrating trust modeling and robot decision-making enables robot behaviors that leverage human trust and actively modulate it for HRC [91]. Building trust through transparency, reliability, and the active involvement of caregivers and patients enhances acceptability. At the same time, public engagement, staff training, and positive case studies foster the adoption of robotics in healthcare [13]. Tasks in healthcare settings, such as elderly care homes [92], vary in complexity and urgency. Future research should develop algorithms for dynamic task allocation based on task criticality, real-time robot capabilities, and human workload levels. For instance, incorporating context-aware AI models could help robots proactively identify when to intervene. This approach would support adaptive workflows that optimize efficiency and care quality, especially in environments with shifting patient needs and staff availability.

Technological advancements play a pivotal role in enabling effective HRC. Advances in sensor technology, including the IoT and the IoRT, have improved robots' perception capabilities, enabling precise and safe interactions in healthcare settings. However, for robots to function reliably in complex healthcare environments, they must possess high situational awareness, allowing them to adapt to dynamic, human-centered interactions and respond to real-time changes in their surroundings [93]. Immersive technologies, such as augmented reality (AR), virtual reality (VR), and mixed reality (MR), have enhanced human-robot collaboration by providing intuitive and interactive interfaces, thereby facilitating better communication and collaboration. Digital twin allows real-time monitoring and control, enhancing precision and safety in robotic-assisted procedures. Artificial Intelligence (AI) enables robots to learn, adapt, and make decisions, improving diagnostic accuracy, personalized care, and overall effectiveness in collaboration with healthcare professionals. Healthcare robots support real-time patient care and monitoring, enhancing efficiency and allowing professionals to focus on complex care activities. They automate routine logistics and hospital operations tasks, streamlining processes and enabling healthcare workers to concentrate on patient-centered care. In rehabilitation, these systems work alongside physiotherapists to deliver consistent, data-informed therapy and support improved outcomes by tailoring recovery programmes to individual patient needs based on therapist-designed plans [94].

Despite advancements in robotics, the successful implementation of robotic systems in practical healthcare applications still needs improvement. Robots in the healthcare industry face acceptance hurdles from multiple stakeholders, including patients, medical staff, family members, and other care providers [95]. This limitation arises primarily from the challenges posed by the unique requirements of diverse hospital environments, which have yet to be systematically collected, analyzed, and addressed. Additionally, cognitive load leads to mental fatigue among healthcare professionals, making it difficult to process visual stimuli or make timely decisions [96].

Ethical and privacy concerns are crucial, as robots handle sensitive patient data and impact decision-making, introducing unique challenges that require thorough examination and resolution [97]. Healthcare robots must handle sensitive patient data responsibly during collaboration, ensuring compliance with regulations such as the Health Insurance Portability and Accountability Act (HIPAA) to protect patient privacy and data security [98]. Furthermore, critical healthcare decisions must remain under caregivers' control, even as robotic systems advance in autonomy. Integration presents technical challenges, such as incorporating robotic systems with existing healthcare infrastructures and ensuring compatibility with other medical devices and systems, which remain complex tasks. Cost is a crucial factor in the adoption and sustainability of HRC systems [99]. The expenses associated with robotic systems may limit accessibility for some healthcare facilities, particularly in low-resource settings, raising concerns about equitable access to cutting-edge healthcare technologies.

Future research should focus on several key areas to address these challenges and enhance HRC in healthcare. Data security is a critical concerns that require strong encryption and anonymization methods to protect patient information [97]. Ethical and privacy concerns must be addressed through robust frameworks that incorporate methodological approaches such as federated learning and differential privacy to ensure data protection and regulatory compliance. To address interoperability challenges, research efforts should prioritise the development of standardised communication protocols, middleware solutions, and open-source platforms that facilitate integration across diverse medical devices and robotic systems. Cost barriers could be addressed by exploring low-cost sensor integration, modular robotic designs, and cloud-based robotics solutions, making these technologies more affordable and accessible to healthcare facilities of all resource levels.

Enhancing reliability through advanced safety features and predictive maintenance is crucial for preventing accidents and ensuring consistent performance. Expanding applications and personalization by researching new areas such as mental health support, chronic disease management, and elderly care will further demonstrate the versatility of HRC. Cross-disciplinary collaboration is essential to address HRC's technical, ethical, and clinical challenges. Future initiatives should establish structured co-design processes involving healthcare workers and patients early in the development lifecycle to ensure systems are aligned with real-world workflows. Moreover, forming joint regulatory technical working groups could help translate clinical guidelines into technical requirements, accelerating safe deployment and improving end-user confidence and compliance. Success factors should be aligned with stages where performance can be measured appropriately [100]. Evaluating collaborative success within healthcare contexts presents an avenue for exploration. Key metrics may include patient health outcomes, operational efficiency improvements, and healthcare provider satisfaction, each offering insights into the impact of HRC. Integrating these metrics can deepen the analysis by underscoring the need for empirical studies that assess collaborative frameworks.

Applying the proposed framework to diverse healthcare contexts, particularly resource-limited settings such as rural areas, presents unique implementation challenges. In these environments, healthcare professional-oriented factors should emphasize simplified task allocation and accessible training programs, ensuring robots complement rather than complicate existing workflows. Patient-centric factors must be adapted to local cultural and social expectations, with the framework leveraging community engagement strategies to enhance trust, acceptance, and responsiveness. System-critical factors necessitate robust, low-power, and easily maintainable robotic solutions that can deliver reliable performance despite infrastructural limitations, such as intermittent connectivity and limited technical support.

While each of the three core components, Healthcare Professional-Oriented, Patient-Centric, and System-Critical, has distinct roles in facilitating successful human-robot collaboration in healthcare, their effectiveness depends on their interactions and mutual influences. Healthcare professionals' trust, teamwork, and effective communication directly impact patient acceptability, safety, and feedback. For instance, when caregivers communicate the robot's role and demonstrate confidence in its capabilities, patients are more likely to feel comfortable and safe during interactions. Conversely, patient feedback and acceptability inform healthcare professionals' task allocation and trust-building efforts, reinforcing positive interaction loops. Patient-centric factors, such as safety and interaction quality, depend on system-critical attributes, including system integration, autonomy, and adaptability. A system designed with robust safety protocols and adaptive learning capabilities will meet patient needs, fostering trust and acceptance. Patient feedback, in turn, provides critical input for refining the system's adaptability to individual patient needs, enhancing overall performance. System autonomy and integration directly influence healthcare professionals' ability to allocate tasks.

VI. Conclusion

This review highlights how Healthcare Professional-Oriented, Patient-Centric, and System-Critical components collectively shape the implementation of robotics in clinical environments. To support practical implementation, the proposed framework offers actionable guidance for key stakeholders. Healthcare administrators can use the framework to assess institutional readiness for HRC by evaluating workforce capacity, communication protocols, and training needs aligned with healthcare professional-oriented factors. Policymakers may leverage the framework to establish regulatory and ethical standards that address patient safety, data privacy, and equitable access, core considerations of the patient-centric and system-critical factors. Technology developers can apply the framework to design robotic systems that are interoperable with clinical infrastructure, responsive to caregiver workflows, and adaptable to patient preferences, thereby aligning technical capabilities with the real-world demands of healthcare. A multidisciplinary approach that integrates technological advancements, ethical considerations, and a design centred around patients and caregivers is essential for fostering widespread adoption and long-term success. Addressing these open challenges will enhance the quality and sustainability of healthcare delivery, enabling practitioners to provide better care through complementary partnerships with robotic technologies. Although HRC in healthcare is still in its early stages, current trends suggest it may become a key driver of resilience, adaptability, and long-term viability.

Acknowledgment

This work is funded by the Strathclyde Studentship project "Intelligent Human-Robot Collaboration for Future Advanced Healthcare Applications" (2023-2026), under studentship number 3090. The author acknowledges the use of generative AI tools, for language refinement and textual improvements in this manuscript. All intellectual contributions, critical analyses, and final revisions were conducted by the authors.

References

[1] G. Yang, Z. Pang, M. J. Deen, M. Dong, Y.-T. Zhang, N. Lovell, and A. M. Rahmani, "Homecare robotic systems for healthcare 4.0: Visions and enabling technologies," *IEEE journal of biomedical and health informatics*, vol. 24, no. 9, pp. 2535–2549, 2020.
[2] M. Y. Shaheen, "Applications of artificial intelligence AI in healthcare: A review," *ScienceOpen Preprints*, 2021.
[3] I. Anghel, T. Cioara, D. Moldovan, M. Antal, C. D. Pop, I. Salomie, C. B. Pop, and V. R. Chifu, "Smart environments and social robots for age-friendly integrated care services," *International journal of environmental research and public health*, vol. 17, no. 11, p. 3801, 2020.
[4] J. T. Licardo, M. Domjan, and T. Orehovački, "Intelligent robotics—a systematic review of emerging technologies and trends," *Electronics*, vol. 13, no. 3, p. 542, 2024.
[5] A. Khan and Y. Anwar, "Robots in healthcare: A survey," in *Advances in Computer Vision: Proceedings of the 2019 Computer Vision Conference (CVC), Volume 2 1*, pp. 280–292, Springer, 2020.
[6] B. Obrenovic, X. Gu, G. Wang, D. Godinic, and I. Jakhongirov, "Generative AI and human–robot interaction: implications and future agenda for business, society and ethics," *AI & SOCIETY*, pp. 1–14, 2024.
[7] A. Giallanza, G. La Scalia, R. Micale, and C. M. La Fata, "Occupational health and safety issues in human-robot collaboration: State of the art and open challenges," *Safety science*, vol. 169, p. 106313, 2024.
[8] R. Gervasi, L. Mastrogiacomo, and F. Franceschini, "A conceptual framework to evaluate human-robot collaboration," *The International Journal of Advanced Manufacturing Technology*, vol. 108, pp. 841–865, 2020.
[9] M. A. Ait Ameur, E. Yang, and S. Brady, "Advancing healthcare through intelligent human-robot collaboration: overview, challenges and opportunities," in *2024 29th International Conference on Automation and Computing (ICAC)*, pp. 1–6, IEEE, 2024.
[10] M. Kyrarini, F. Lygerakis, A. Rajavenkatanarayanan, C. Sevastopoulos, H. R. Nambiappan, K. K. Chaitanya, A. R. Babu, J. Mathew, and F. Makedon, "A survey of robots in healthcare," *Technologies*, vol. 9, no. 1, p. 8, 2021.

[11] C. Esterwood and L. P. Robert, "A systematic review of human and robot personality in health care human-robot interaction," *Frontiers in Robotics and AI*, vol. Volume 8 - 2021, 2021.

[12] S. A. Green, M. Billinghurst, X. Chen, and J. G. Chase, "Human-robot collaboration: A literature review and augmented reality approach in design," *International journal of advanced robotic systems*, vol. 5, no. 1, pp. 1–19, 2008.

[13] K. Cresswell, S. Cunningham-Burley, and A. Sheikh, "Health care robotics: qualitative exploration of key challenges and future directions," *Journal of Medical Internet Research*, vol. 20, no. 7, 2018. e10410.

[14] Y. Lai, A. Kankanhalli, and D. Ong, "Human-AI collaboration in healthcare: A review and research agenda," in *Proceedings of the Hawaii International Conference on System Sciences*, 2021.

[15] I. N. Weerarathna, D. Raymond, and A. Luharia, "Human-robot collaboration for healthcare: A narrative review," *Cureus*, vol. 15, no. 11, 2023.

[16] D. Silvera-Tawil, "Robotics in healthcare: A survey," *SN Computer Science*, vol. 5, no. 1, p. 189, 2024.

[17] N. Deo and A. Anjankar, "Artificial intelligence with robotics in healthcare: a narrative review of its viability in india," *Cureus*, vol. 15, no. 5, 2023.

[18] S. Martin, E. Davies, and B. Gershlick, *Under pressure*. Health Foundation, 2016.

[19] G. A. Kebede, A. A. Gelaw, H. Andualem, and A. T. Hailu, "Review of the characteristics of mobile robots for health care application," *International Journal of Intelligent Robotics and Applications*, pp. 1–23, 2024.

[20] A. A. Morgan, J. Abdi, M. A. Syed, G. E. Kohen, P. Barlow, and M. P. Vizcaychipi, "Robots in healthcare: a scoping review," *Current robotics reports*, vol. 3, no. 4, pp. 271–280, 2022.

[21] S. Chatterjee, S. Das, K. Ganguly, and D. Mandal, "Advancements in robotic surgery: innovations, challenges and future prospects," *Journal of Robotic Surgery*, vol. 18, no. 1, p. 28, 2024.

[22] W. Bauer, M. Bender, M. Braun, P. Rally, and O. Scholtz, "Lightweight robots in manual assembly–best to start simply," *Frauenhofer-Institut für Arbeitswirtschaft und Organisation IAO, Stuttgart*, vol. 1, 2016.

[23] H. Momattin, S. Arafa, S. Momattin, R. Rahal, and J. Waterson, "Robotic pharmacy implementation and outcomes in Saudi Arabia: a 21-month usability study," *JMIR Human Factors*, vol. 8, no. 3, 2021. e28381.

[24] F. Astrid, Z. Beata, E. Julia, P. Elisabeth, and D.-E. Magda, "The use of a UV-C disinfection robot in the routine cleaning process: a field study in an academic hospital," *Antimicrobial Resistance & Infection Control*, vol. 10, no. 1, p. 84, 2021.

[25] K. Tornbjerg, A. M. Kanstrup, M. B. Skov, and M. Rehm, "Investigating human-robot cooperation in a hospital environment: Scrutinising visions and actual realisation of mobile robots in service work," in *Proceedings of the 2021 ACM Designing Interactive Systems Conference*, pp. 381–391, 2021.

[26] A. Brinkmann, C. F.-v. Böhlen, C. Kowalski, S. Lau, O. Meyer, R. Diekmann, and A. Hein, "Providing physical relief for nurses by collaborative robotics," *Scientific Reports*, vol. 12, no. 1, p. 8644, 2022.

[27] J. Al-Jaroodi, N. Mohamed, and E. Abukhousa, "Health 4.0: on the way to realizing the healthcare of the future," *IEEE Access*, vol. 8, pp. 211189–211210, 2020.

[28] G. P. Soriano, Y. Yasuhara, H. Ito, K. Matsumoto, K. Osaka, Y. Kai, R. Locsin, S. Schoenhofer, and T. Tanioka, "Robots and robotics in nursing," in *Healthcare*, vol. 10, p. 1571, MDPI, 2022.

[29] V. Kostrubiec, C. Lajunta, P.-V. Paubel, and J. Kruck, "Does the social robot nao facilitate cooperation in high functioning children with ASD?," *International Journal of Social Robotics*, vol. 16, no. 2, pp. 281–298, 2024.

[30] D. L. Johanson, H. S. Ahn, and E. Broadbent, "Improving interactions with healthcare robots: a review of communication behaviours in social and healthcare contexts," *International Journal of Social Robotics*, vol. 13, no. 8, pp. 1835–1850, 2021.

[31] M. S. Kaiser, S. Al Mamun, M. Mahmud, and M. H. Tania, "Healthcare robots to combat COVID-19," *COVID-19: Prediction, decision-making, and its impacts*, pp. 83–97, 2021.

[32] I. Shanks, M. L. Scott, M. Mende, J. van Doorn, and D. Grewal, "Cobotic service teams and power dynamics: Understanding and mitigating unintended consequences of human-robot collaboration in healthcare services," *Journal of the Academy of Marketing Science*, pp. 1–27, 2024.

[33] D. Townsend and A. MajidiRad, "Trust in human-robot interaction within healthcare services: A review study," in *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, vol. 86281, p. V007T07A030, American Society of Mechanical Engineers, 2022.

[34] L. Grespan, P. Fiorini, G. Colucci, L. Grespan, P. Fiorini, and G. Colucci, "Patient safety in robotic surgery," *The Route to Patient Safety in Robotic Surgery*, pp. 7–23, 2019.

[35] S. K. Hopko, Y. Zhang, A. Yadav, P. R. Pagilla, and R. K. Mehta, "Brain–behavior relationships of trust in shared space human–robot collaboration," *ACM Transactions on Human-Robot Interaction*, vol. 13, no. 1, pp. 1–23, 2024.

[36] J. Kraus, L. Miller, M. Klumpp, F. Babel, D. Scholz, J. Merger, and M. Baumann, "On the role of beliefs and trust for the intention to use service robots: an integrated trustworthiness beliefs model for robot acceptance," *International Journal of Social Robotics*, vol. 16, no. 6, pp. 1223–1246, 2024.

[37] U. Maniscalco, A. Messina, and P. Storniolo, "The human–robot interaction in robot-aided medical care," in *Human Centred Intelligent Systems: Proceedings of KES-HCIS 2020 Conference*, pp. 233–242, Springer, 2021.

[38] R. ISO13482, "robotic devices-safety requirements for personal care robots," *International Organization for Standardization*, 2014.

[39] A. Grob, "Setting standards: The IEC 60601 series: Quick-use guide," *Biomedical Instrumentation & Technology*, vol. 54, no. 3, pp. 220–222, 2020.

[40] O. E. Sorokoletova and L. Iocchi, "Enhancing robot reliability for health-care facilities by means of human-aware navigation planning," *arXiv preprint arXiv:2409.17131*, 2024.

[41] H. Habehh and S. Gohel, "Machine learning in healthcare," *Current Genomics*, vol. 22, no. 4, pp. 291–300, 2021.

[42] J. Marchang and A. Di Nuovo, "Assistive multimodal robotic system (AMRSys): security and privacy issues, challenges, and possible solutions," *Applied Sciences*, vol. 12, no. 4, p. 2174, 2022.

[43] R. Iphofen and M. Kritikos, "Regulating artificial intelligence and robotics: ethics by design in a digital society," *Contemporary Social Science*, vol. 16, no. 2, pp. 170–184, 2021.

[44] C. Bartneck, C. Lütge, A. Wagner, and S. Welsh, *An introduction to ethics in robotics and AI*. Springer Nature, 2021.

[45] T. Haidegger, "Autonomy for surgical robots: Concepts and paradigms," *IEEE Transactions on Medical Robotics and Bionics*, vol. 1, no. 2, pp. 65–76, 2019.

[46] A. Iglesias, R. Viciana, J. M. Pérez-Lorenzo, K. L. H. Ting, A. Tudela, R. Marfil, M. Qbilat, A. Hurtado, A. Jerez, and J. P. Bandera, "The town crier: A use-case design and implementation for a socially assistive robot in retirement homes," *Robotics*, vol. 13, no. 4, p. 61, 2024.

[47] F. Gongor and O. Tutsoy, "On the remarkable advancement of assistive robotics in human-robot interaction-based health-care applications: An exploratory overview of the literature," *International Journal of Human–Computer Interaction*, pp. 1–41, 2024.

[48] C. L. Kok, C. K. Ho, T. H. Teo, K. Kato, and Y. Y. Koh, "A novel implementation of a social robot for sustainable human engagement in homecare services for ageing populations," *Sensors*, vol. 24, no. 14, p. 4466, 2024.

[49] Q. Yang, "Edge computing based human-robot cognitive fusion: A medical case study in the autism spectrum disorder therapy," *arXiv preprint arXiv:2401.00776*, 2024.

[50] L.-C. Lu, S.-H. Lan, Y.-P. Hsieh, L.-Y. Lin, S.-J. Lan, and J.-C. Chen, "Effectiveness of companion robot care for dementia: a systematic review and meta-analysis," *Innovation in aging*, vol. 5, no. 2, p. igab013, 2021.

[51] H. Yeganeh, "An analysis of emerging trends and transformations in global healthcare," *International Journal of Health Governance*, vol. 24, no. 2, pp. 169–180, 2019.

[52] A. Amarillo, E. Sanchez, J. Caceres, and J. Oñativia, "Collaborative human–robot interaction interface: Development for a spinal surgery robotic assistant," *International Journal of Social Robotics*, vol. 13, no. 6, pp. 1473–1484, 2021.

[53] J. Fu, M. Pecorella, E. Iovene, M. C. Palumbo, A. Rota, A. Redaelli, G. Ferrigno, and E. De Momi, "Augmented reality and human–robot collaboration framework for percutaneous nephrolithotomy: System design, implementation, and performance metrics," *IEEE Robotics & Automation Magazine*, 2024.

[54] K. Catchpole, T. Cohen, M. Alfred, S. Lawton, F. Kanji, D. Shouhed, L. Nemeth, and J. Anger, "Human factors integration in robotic surgery," *Human Factors*, vol. 66, no. 3, pp. 683–700, 2024.

[55] J. Yang, J. A. Barragan, J. M. Farrow, C. P. Sundaram, J. P. Wachs, and D. Yu, "An adaptive human-robotic interaction architecture for augmenting surgery performance using real-time workload

sensing—demonstration of a semi-autonomous suction tool," *Human Factors*, vol. 66, no. 4, pp. 1081–1102, 2024.

[56] X. Zhang, J. Yu, J. Zhu, H. Wei, N. Meng, M. Hu, and J. Tang, "A meta-analysis of unilateral axillary approach for robotic surgery compared with open surgery for differentiated thyroid carcinoma," *Plos one*, vol. 19, no. 4, p. e0298153, 2024.

[57] J. Leoste, K. Strömberg-Järvis, T. Robal, K. Marmor, K. Kangur, and A.-M. Rebane, "Testing scenarios for using telepresence robots in healthcare settings," *Computational and Structural Biotechnology Journal*, vol. 24, pp. 105–114, 2024.

[58] K. M. Huun and J. E. Slaven, "Robotic telepresence and face-to-face collaborative nursing simulation: A correlational, cross-sectional study," *Clinical Simulation in Nursing*, vol. 90, p. 101525, 2024.

[59] J. Laigaard, T. U. Fredskild, and G. L. Fojecki, "Telepresence robots at the urology and emergency department: a pilot study assessing patients' and healthcare workers' satisfaction," *International journal of telemedicine and applications*, vol. 2022, no. 1, p. 8787882, 2022.

[60] P. Dhivya, V. Karthiga, S. Vinotha, S. Saravanakumar, T. Abinith, and T. Varunsri, "Advanced sensing and actuation health monitoring robot," in *2024 5th International Conference on Electronics and Sustainable Communication Systems (ICESC)*, pp. 177–183, IEEE, 2024.

[61] A. Ikpe, J. Ohwoekevwo, and I. Ekanem, "Overview of the role of medical robotics in day-to-day healthcare services: A paradigm shift in clinical operations," *Ibom Medical Journal*, vol. 17, no. 2, pp. 192–203, 2024.

[62] G. T. Babalola, J.-M. Gaston, J. Trombetta, and S. Tulk Jesso, "A systematic review of collaborative robots for nurses: where are we now, and where is the evidence?," *Frontiers in Robotics and AI*, vol. 11, p. 1398140, 2024.

[63] D. Sommer, J. Kasbauer, D. Jakob, S. Schmidt, and F. Wahl, "Potential of assistive robots in clinical nursing: An observational study of nurses' transportation tasks in rural clinics of bavaria, germany," *Nursing Reports*, vol. 14, no. 1, pp. 267–286, 2024.

[64] L. Bernhard, P. Schwingenschlögl, J. Hofmann, D. Wilhelm, and A. Knoll, "Boosting the hospital by integrating mobile robotic assistance systems: a comprehensive classification of the risks to be addressed," *Autonomous Robots*, vol. 48, no. 1, p. 1, 2024.

[65] T. F. Urbine and P. J. Schneider, "Estimated cost savings from reducing errors in the preparation of sterile doses of medications," *Hospital pharmacy*, vol. 49, no. 8, pp. 731–739, 2014.

[66] G. Cheng, Y. Huang, X. Zhang, H. Chen, and J. Ota, "An overview of transfer nursing robot: Classification, key technology, and trend," *Robotics and Autonomous Systems*, vol. 174, p. 104653, 2024.

[67] M. J. Sobrepera, A. T. Nguyen, E. S. Gavin, and M. J. Johnson, "Insights into the deployment of a social robot-augmented telepresence robot in an elder care clinic–perspectives from patients and therapists: a pilot study," *Robotica*, vol. 42, no. 5, pp. 1321–1349, 2024.

[68] J. Li, X. Gu, S. Qiu, X. Zhou, A. Cangelosi, C. K. Loo, and X. Liu, "A survey of wearable lower extremity neurorehabilitation exoskeleton: Sensing, gait dynamics, and human–robot collaboration," *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, 2024.

[69] A. D. Banyai and C. Brișan, "Robotics in physical rehabilitation: Systematic review," in *Healthcare*, vol. 12, p. 1720, MDPI, 2024.

[70] G. Carpino, A. Pezzola, M. Urbano, and E. Guglielmelli, "Assessing effectiveness and costs in robot-mediated lower limbs rehabilitation: a meta-analysis and state of the art," *Journal of healthcare engineering*, vol. 2018, no. 1, p. 7492024, 2018.

[71] S. S. Dhanwe, C. M. Abhangrao, and K. K. S. Liyakat, "AI-driven iot in robotics: A review," *Journal of Mechanical Robotics*, vol. 9, no. 1, pp. 41–48, 2024.

[72] A. Kumar and S. Sharma, "Internet of robotic things: Design and develop the quality of service framework for the healthcare sector using coap," *IAES International Journal of Robotics and Automation*, vol. 10, no. 4, p. 289, 2021.

[73] Y. Qiu, A. Ashok, C. C. Nguyen, Y. Yamauchi, T. N. Do, and H.-P. Phan, "Integrated sensors for soft medical robotics," *Small*, p. 2308805, 2024.

[74] S. Gross and B. Krenn, "A communicative perspective on human–robot collaboration in industry: Mapping communicative modes on collaborative scenarios," *International Journal of Social Robotics*, vol. 16, no. 6, pp. 1315–1332, 2024.

[75] S. Ness, T. R. Xuan, and O. O. Oguntibeju, "Influence of AI: Robotics in healthcare," *Asian Journal of Research in Computer Science*, vol. 17, no. 5, pp. 222–237, 2024.

[76] F. Zanatta, A. Giardini, A. Pierobon, M. D'Addario, and P. Steca, "A systematic review on the usability of robotic and virtual reality devices in neuromotor rehabilitation: patients' and healthcare professionals' perspective," *BMC health services research*, vol. 22, no. 1, p. 523, 2022.

[77] Y.-P. Su, X.-Q. Chen, T. Zhou, C. Pretty, and G. Chase, "Mixed-reality-enhanced human–robot interaction with an imitation-based mapping approach for intuitive teleoperation of a robotic arm-hand system," *Applied Sciences*, vol. 12, no. 9, p. 4740, 2022.

[78] A. Lastrucci, Y. Wandael, A. Barra, R. Ricci, G. Maccioni, A. Pirrera, and D. Giansanti, "Exploring augmented reality integration in diagnostic imaging: Myth or reality?," *Diagnostics*, vol. 14, no. 13, p. 1333, 2024.

[79] P. Gahelot, R. Chhabra, and G. Singh, "Systematic review on the use of immersive technologies in healthcare," in *2024 IEEE International Conference on Computing, Power and Communication Technologies (IC2PCT)*, vol. 5, pp. 878–882, IEEE, 2024.

[80] I. Maglogiannis, F. Trastelis, M. Kalogeropoulos, A. Khan, P. Gallos, A. Menychtas, C. Panagopoulos, P. Papachristou, N. Islam, A. Wolff, *et al.*, "AI4work project: Human-centric digital twin approaches to trustworthy AI and robotics for improved working conditions in healthcare and education sectors," *Stud. Health Technol. Inform*, vol. 316, pp. 1013–1017, 2024.

[81] A. Trabelsi, J. Sandoval, A. Mlika, S. Lahouar, and M. A. Laribi, "Design and implementation of a digital twin for a multi-robot surgical platform," in *IFToMM International Symposium on Robotics and Mechatronics*, pp. 207–216, Springer, 2024.

[82] C. Rajurkar, B. Murugan, and G. P. Namasivayam, "Design and integration of iort-enabled robotic systems with wearable devices in a digital twin framework," in *2024 9th International Conference on Control and Robotics Engineering (ICCRE)*, pp. 45–49, IEEE, 2024.

[83] G. Yang, Z. Ye, H. Wu, C. Li, R. Wang, D. Kong, Z. Hou, H. Wang, X. Huang, Z. Pang, *et al.*, "A digital twin based large-area robot skin system for safer human-centered healthcare robots toward healthcare 4.0," *IEEE Transactions on Medical Robotics and Bionics*, 2024.

[84] Z. Shi, E. Landrum, A. O'Connell, M. Kian, L. Pinto-Alva, K. Shrestha, X. Zhu, and M. J. Matarić, "How can large language models enable better socially assistive human-robot interaction: A brief survey," in *Proceedings of the AAAI Symposium Series*, vol. 3, pp. 401–404, 2024.

[85] A. Bohr and K. Memarzadeh, "The rise of artificial intelligence in healthcare applications," in *Artificial Intelligence in healthcare*, pp. 25–60, Elsevier, 2020.

[86] J. A. Duncan, F. Alambeigi, and M. W. Pryor, "A survey of multimodal perception methods for human-robot interaction in social environments," *ACM Transactions on Human-Robot Interaction*, 2024.

[87] F. Soljacic, T. Law, M. Chita-Tegmark, and M. Scheutz, "Robots in healthcare as envisioned by care professionals," *Intelligent Service Robotics*, pp. 1–17, 2024.

[88] M. N. Al-Hamadani, M. A. Fadhel, L. Alzubaidi, and B. Harangi, "Reinforcement learning algorithms and applications in healthcare and robotics: A comprehensive and systematic review," *Sensors*, vol. 24, no. 8, p. 2461, 2024.

[89] R. M. Ratwani, K. Sutton, and J. E. Galarraga, "Addressing AI algorithmic bias in health care," *JAMA*, vol. 332, no. 13, pp. 1051–1052, 2024.

[90] T. Kaupp, A. Makarenko, and H. Durrant-Whyte, "Human–robot communication for collaborative decision making—a probabilistic approach," *Robotics and Autonomous Systems*, vol. 58, no. 5, pp. 444–456, 2010.

[91] M. Chen, S. Nikolaidis, H. Soh, D. Hsu, and S. Srinivasa, "Planning with trust for human-robot collaboration," in *Proceedings of the 2018 ACM/IEEE international conference on human-robot interaction*, pp. 307–315, 2018.

[92] G. P. Das, T. M. McGinnity, S. A. Coleman, and L. Behera, "A distributed task allocation algorithm for a multi-robot system in healthcare facilities," *Journal of Intelligent & Robotic Systems*, vol. 80, pp. 33–58, 2015.

[93] M. Müller, T. Ruppert, N. Jazdi, and M. Weyrich, "Self-improving situation awareness for human–robot-collaboration using intelligent digital twin," *Journal of Intelligent Manufacturing*, vol. 35, no. 5, pp. 2045–2063, 2024.

[94] E. M. V. Cruz, S. Oliveira, and A. Correia, "Robotics applications in the hospital domain: A literature review," *Applied System Innovation*, vol. 7, no. 6, p. 125, 2024.

[95] D. E. Kalisz, I. Khelladi, S. Castellano, and R. Sorio, "The adoption, diffusion & categorical ambiguity trifecta of social robots in e-health–insights from healthcare professionals," *Futures*, vol. 129, p. 102743, 2021.

[96] Y. Yan and Y. Jia, "A review on human comfort factors, measurements, and improvements in human–robot collaboration," *Sensors*, vol. 22, no. 19, p. 7431, 2022.

[97] C. Elendu, D. C. Amaechi, T. C. Elendu, K. A. Jingwa, O. K. Okoye, M. J. Okah, J. A. Ladele, A. H. Farah, and H. A. Alimi, "Ethical implications of AI and robotics in healthcare: A review," *Medicine*, vol. 102, no. 50, 2023. e36671.

[98] S. Doss, R. Pawar, and R. Maddireddy, "Intelligent automation in health insurance," *Bimaquest*, vol. 22, no. 1, 2022.

[99] G. Michalos, P. Karagiannis, N. Dimitropoulos, D. Andronas, and S. Makris, "Human robot collaboration in industrial environments," *The 21st century industrial robot: When tools become collaborators*, pp. 17–39, 2022.

[100] T. Kopp, M. Baumgartner, and S. Kinkel, "Success factors for introducing industrial human-robot interaction in practice: an empirically driven framework," *The International Journal of Advanced Manufacturing Technology*, vol. 112, pp. 685–704, 2021.