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REVIEW ARTICLE

A Review on Human-Robot Interaction and User Experience in Smart Robotic Wheelchairs

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Abstract
This review research paper provides an analysis of the current state of Human-Robot Interaction (HRI) and User Experience (UX) in the context of smart robotic wheelchairs. It explores the advancements in HRI techniques, including multimodal interfaces, gesture recognition, voice commands, and brain-computer interfaces, and evaluates their impact on user experience factors such as usability, learnability, efficiency, and satisfaction. The paper discusses the role of artificial intelligence and machine learning in enhancing HRI capabilities and personalization of wheelchair behavior. The review highlights gaps in current research and identifies future directions to improve the immersive experience of smart wheelchair users. Overall, this comprehensive review contributes to a deeper understanding of the factors influencing user acceptance, satisfaction, and system performance, guiding the development of more intuitive and user-centered smart robotic wheelchairs for individuals with mobility impairments.

Keywords: Smart Robotic Wheelchairs**,** Assistive Technology**,** Multimodal Interfaces**,** Brain-Computer Interfaces**,** User Satisfaction

Introduction

The need for smart robotic wheelchairs has become increasingly apparent in recent years, driven by the growing demand to improve the quality of life and independence of individuals with mobility impairments. Traditional manual wheelchairs have limitations in terms of maneuverability, control, and interaction, leading to challenges in performing daily activities and engaging in social interactions (Sahoo and Choudhury, 2021). Smart robotic wheelchairs offer a promising solution by integrating advanced technologies such as robotics, artificial intelligence, and human-robot interaction to enhance mobility, accessibility, and user experience.

One of the primary motivations for developing smart robotic wheelchairs is to provide individuals with greater autonomy and independence in navigating their environment (Padfield et al., 2023). These wheelchairs are equipped with sensors and intelligent control systems that enable autonomous navigation and obstacle detection, allowing users to move safely and efficiently in various indoor and outdoor environments. By reducing the reliance on caregivers or assistance, smart robotic wheelchairs empower individuals with disabilities to have greater control over their own mobility, boosting their self-confidence and overall well-being (Gracia et al., 2023).

Moreover, smart robotic wheelchairs address the need for improved human-robot interaction. Conventional wheelchairs often require significant physical effort and manual control, which can be challenging for individuals with limited upper body strength or dexterity. Smart robotic wheelchairs offer intuitive interfaces, such as voice commands, gesture recognition, or brain-computer interfaces, enabling users to control the wheelchair effortlessly and efficiently (Houssein et al., 2022). These advanced interaction modalities enhance the user experience, making the wheelchair operation more natural, personalized, and user-friendly.

Additionally, smart robotic wheelchairs aim to provide a higher level of adaptability and customization. Each individual has unique mobility requirements and preferences. Smart wheelchairs can learn from user behavior, adapt their movement patterns, and personalize their responses accordingly (Sahoo and Choudhury, 2023a). For instance, they can adjust the speed, acceleration, or turning radius based on the user's comfort level or specific needs. This adaptability ensures a more tailored and comfortable experience for wheelchair users, enhancing their overall satisfaction and acceptance of the technology.

The development and adoption of smart robotic wheelchairs address the pressing need to enhance mobility, independence, and user experience for individuals with mobility impairments. By integrating advanced technologies and focusing on human-robot interaction, these wheelchairs offer intuitive control interfaces, autonomous navigation, adaptability, and customization to meet the unique needs of each user. As research and innovation in this field continue to progress, smart robotic wheelchairs hold immense potential in revolutionizing mobility assistance and improving the quality of life for individuals with disabilities.

Significance of the proposed study

The significance of focusing on Human-Robot Interaction (HRI) and User Experience (UX) in smart robotic wheelchairs lies in their potential to enhance independence, accessibility, and overall user satisfaction for individuals with mobility impairments. By developing intuitive interfaces, personalized interactions, and adaptive behaviors, these advancements contribute to the following key aspects:

- Independence and Mobility: Smart robotic wheelchairs equipped with advanced HRI techniques empower users with greater control, allowing them to navigate their environment independently (Machado et al., 2023). This promotes self-reliance, boosts confidence, and improves overall mobility for individuals with disabilities.
- Accessibility and Inclusion: By integrating multimodal interfaces and considering diverse user needs, smart robotic wheelchairs ensure accessibility for individuals with varying abilities and preferences(Sahoo and Choudhury, 2023b). These wheelchairs enhance inclusion, enabling a wider range of users to effectively interact with and operate the technology.
- User Satisfaction and Acceptance: Focusing on UX in smart robotic wheelchairs leads to improved user satisfaction, acceptance, and adoption of these assistive devices(Sahoo and Choudhury, 2023c). Intuitive interfaces, easy learnability, and personalized experiences contribute to higher levels of user satisfaction, resulting in increased user acceptance and long-term use.
- Personalization and Adaptability: Smart robotic wheelchairs that employ AI and machine learning algorithms can adapt to individual user preferences, providing a tailored experience (Hemmati and Rahmani, 2022). By personalizing movement patterns and responses, these wheelchairs enhance comfort, efficiency, and overall user experience.

Focusing on HRI and UX in smart robotic wheelchairs significantly improves the quality of life for individuals with mobility impairments. By promoting independence, accessibility, user satisfaction, safety, and social acceptance, these advancements contribute to a more inclusive society and empower individuals to lead fulfilling lives.

Objective for the proposed study

The objective of this review research paper is to comprehensively analyze and evaluate the current state of research on Human-Robot Interaction (HRI) and User Experience (UX) in the domain of smart robotic wheelchairs. The paper aims to achieve the following specific objectives:

- To summarize and synthesize recent advancements in HRI techniques and UX considerations in smart robotic wheelchairs, including multimodal interfaces, gesture recognition, voice commands, brain-computer interfaces, and adaptive behaviors.
- To evaluate the impact of different HRI strategies on user experience factors such as usability, learnability, efficiency, and satisfaction in the context of smart robotic wheelchairs.
- To provide insights and recommendations to guide researchers, engineers, and designers in developing more intuitive, user-centered, and accessible smart robotic wheelchairs, with a

focus on enhancing user satisfaction, acceptance, and overall system performance.

By achieving these objectives, this review research paper aims to contribute to a deeper understanding of the current state-of-the-art in HRI and UX in smart robotic wheelchairs, and provide valuable insights for future research and development in this rapidly evolving field.

Literature review

Smart robotic wheelchairs have emerged as a promising solution for enhancing mobility and independence in individuals with mobility impairments. This literature review aims to provide an overview of the current state of research on smart robotic wheelchairs, focusing on the advancements in technology, human-robot interaction (HRI), user experience (UX), and the impact on users' quality of life.

Smart robotic wheelchairs incorporate advanced technologies such as robotics, artificial intelligence, and sensor systems to improve functionality and user experience. Torres-Vega et al. (2023) developed a smart wheelchair with a visual tracking system that uses computer vision algorithms to detect and track objects, allowing for autonomous navigation. This technology enables users to navigate crowded environments safely. Effective human-robot interaction plays a vital role in improving user experience in smart robotic wheelchairs. Sadi et al. (2022) investigated the use of gesture recognition techniques in wheelchair control. Their study demonstrated that gesture-based control interfaces enhanced user satisfaction and provided a more intuitive interaction modality.

Usability, learnability, efficiency, and satisfaction are crucial aspects of user experience in smart robotic wheelchairs. Zhang et al. (2023) conducted a study to evaluate the usability and user satisfaction of a smart robotic wheelchair with voice command capabilities. The results showed that the voice command interface improved the ease of use and overall satisfaction of the users. Personalizing smart robotic wheelchairs based on individual user needs and preferences is essential for enhancing user experience. Darko et al. (2022) proposed a personalized control system for smart wheelchairs using machine learning techniques. Their system adapted the control parameters to individual user characteristics, leading to improved comfort and usability.

Previous studies on Human-Robot Interaction

Smart robotic wheelchairs have revolutionized the field of assistive technology by integrating robotic capabilities into traditional wheelchairs, providing enhanced mobility and independence for individuals with mobility impairments. Effective human-robot interaction (HRI) is critical for optimizing the control, navigation, and collaboration between users and smart robotic wheelchairs.

Several challenges arise in achieving seamless HRI in smart robotic wheelchairs. Control interfaces play a vital role in facilitating user operation, and conventional methods such as joysticks and touchscreens have been widely used (Xu et al., 2023). However, recent developments have explored novel approaches, including voice commands and gesture recognition, to enhance usability and accessibility (Lv et al., 2020). Navigation and obstacle avoidance are crucial aspects of smart robotic wheelchairs, demanding advanced sensor technologies such as cameras, LiDAR, and ultrasonic sensors (Sahoo and Goswami, 2023). Path planning algorithms and collision avoidance mechanisms contribute to safe and efficient navigation (Ntakolia et al., 2023). Adaptability and personalization are essential for accommodating individual user preferences and capabilities. Adjustable seating positions and customizable control interfaces have been incorporated to enhance user comfort and satisfaction (Avutu et al., 2023). Feedback and communication mechanisms, including auditory, visual, and haptic feedback, enable effective communication between the user and the wheelchair, conveying vital information about the wheelchair's status and environment (Su et al., 2023). Safety and trust are paramount, and features such as collision detection, emergency stop mechanisms, and fail-safe systems ensure user safety and build trust in the technology (Zacharaki et al., 2020).

Technological advancements have greatly influenced HRI in smart robotic wheelchairs. Machine learning and artificial intelligence techniques have enabled adaptive behavior and improved user-machine interaction (Tomari et al., 2012). Sensor fusion and perception algorithms have enhanced the wheelchair's perception capabilities, enabling accurate obstacle detection and environment understanding (Pradeep et al., 2022).

Past studies on User Experience

Smart robotic wheelchairs have revolutionized the field of assistive technology, providing individuals with mobility impairments enhanced mobility and independence. User experience (UX) plays a critical role in the acceptance and long-term use of these devices. Several factors contribute to the overall user experience in smart robotic wheelchairs. Understanding these factors is crucial for designing user-centered systems that meet the unique needs and preferences of wheelchair users.

The ease of use and learnability of smart robotic wheelchairs are essential for ensuring that users can operate the device intuitively and with minimal training (Poirier et al., 2023). Intuitive control interfaces and clear instructions contribute to a positive user experience, enabling individuals to navigate and control the wheelchair with confidence.

Comfort and ergonomics play a significant role in enhancing the user experience. Wheelchair users often spend extended periods in their chairs, making factors such as proper cushioning, lumbar support, and adjustability critical for user comfort and well-being (Sahoo and Goswami, 2024). Customizable seating positions and ergonomic design elements further enhance user satisfaction. Safety and reliability are paramount concerns for wheelchair users. Smart robotic wheelchairs should incorporate robust safety features, including collision detection, emergency stop mechanisms, and fail-safe systems (Graf and Eckstein, 2023). Ensuring user safety and building trust in the technology contribute to a positive user experience and promote user acceptance.

Factors such as ease of use, comfort, safety, aesthetics, and long-term engagement play crucial roles in enhancing the overall user experience. Designing user-centered systems that address these factors is essential for ensuring user acceptance and satisfaction. Future research should focus on refining and improving these aspects of UX in smart robotic wheelchairs, thereby empowering individuals with mobility impairments and enhancing their quality of life.

Research gap and Novelty

Despite the significant advancements in the field of smart robotic wheelchairs, there are still several research gaps that need to be addressed. One prominent research gap lies in the limited focus on real-world deployment scenarios. While many existing studies on human-robot interaction (HRI) and user experience (UX) in smart robotic wheelchairs have been conducted in controlled laboratory settings, the practical usability and effectiveness of these devices in real-world environments remain largely unexplored. Factors such as varying environmental conditions, social interactions, and complex navigation scenarios need to be considered to ensure the seamless integration of smart robotic wheelchairs into users' daily lives.

Another research gap is the lack of long-term user studies. Most studies have focused on short-term evaluations, providing valuable insights into immediate user experiences with smart robotic wheelchairs. However, to truly understand the impact of these devices on user well-being, user acceptance, and continued use, it is essential to conduct long-term user studies. These studies can shed light on the sustained usability, user satisfaction, and quality of life improvements that individuals with mobility impairments experience over extended periods of time. Additionally, there is a need for a more comprehensive user-centered design approach in the development of smart robotic wheelchairs. While some studies have incorporated user preferences and needs into the design process, a more systematic and inclusive approach is required. Involving end-users, such as individuals with mobility impairments and healthcare professionals, from the early stages of design and development can ensure that smart robotic wheelchairs truly meet their requirements, expectations, and desires.

This review paper brings together the fields of human-robot interaction (HRI) and user experience (UX) within the context of smart robotic wheelchairs, offering novel insights into their interplay. By comprehensively integrating HRI and UX, this paper provides a holistic understanding of how effective interaction influences user satisfaction and overall experience with these devices. The paper's novelty lies in its identification and highlighting of the research gaps that currently exist in the literature on HRI and UX in smart robotic wheelchairs. By pinpointing the need for real-world deployment studies, long-term user evaluations, and a more comprehensive user-centered design approach, it offers a roadmap for future research in this field. These identified research gaps create opportunities for researchers, engineers, and designers to explore and address these areas, ultimately advancing the field of smart robotic wheelchairs.

Furthermore, this review paper goes beyond academic discussions and offers practical implications for the design and development of smart robotic wheelchairs. By discussing key factors influencing HRI and UX, such as control interfaces, navigation capabilities, adaptability, feedback systems, safety features, and aesthetics, it provides actionable recommendations. These practical insights can guide researchers and designers in creating user-centered smart robotic wheelchair systems that are tailored to the unique needs and preferences of individuals with mobility impairments. By addressing these research gaps and providing practical insights, this review paper contributes to the advancement of HRI and UX in the field of smart robotic wheelchairs. It sets the stage for further research, development, and innovation, ultimately improving the lives of individuals with mobility impairments by promoting their independence, mobility, and overall well-being.

Human-Robot Interaction in Smart Robotic Wheelchairs

Human-robot interaction (HRI) plays a crucial role in the design and operation of smart robotic wheelchairs, offering individuals with mobility impairments enhanced mobility, independence, and improved quality of life. Smart robotic wheelchairs integrate robotic capabilities and advanced technologies, enabling seamless interaction between users and the wheelchair. Effective HRI in these devices involves designing intuitive control interfaces, enabling safe and efficient navigation, providing personalized and adaptive functionalities, and promoting user satisfaction. This short introduction sets the stage for exploring the significance of HRI in smart robotic wheelchairs, highlighting the key challenges, technological advancements, and opportunities for improving the user experience.

Gesture recognition interfaces

Gesture recognition interfaces are an emerging technology in the field of human-robot interaction (HRI) for smart robotic wheelchairs. These interfaces allow users to control and interact with the wheelchair through natural hand and body movements, offering an intuitive and accessible means of operation (Savur and Sahin, 2023). Gesture recognition interfaces utilize computer vision and machine learning techniques to interpret and understand user gestures, enabling the wheelchair to respond accordingly.

The process of gesture recognition involves multiple stages. First, a sensor, such as a camera or depth sensor, captures the user's movements. Computer vision algorithms then extract relevant features from the captured data, such as hand position, orientation, and motion trajectories (Soraa, 2023). These features are then mapped to predefined gestures or commands through machine learning algorithms, which classify and interpret the user's intentions.

Gesture recognition interfaces offer several advantages in the context of smart robotic wheelchairs. Firstly, they provide a more natural and intuitive means of interaction, mimicking human-human communication. Users can express their commands and preferences through familiar gestures, reducing the learning curve and cognitive load associated with other control interfaces. This can be particularly beneficial for individuals with limited dexterity or motor control. Moreover, gesture recognition interfaces enhance accessibility, as they do not require physical contact or fine motor skills to operate. Users can interact with the wheelchair using larger body movements or gestures, accommodating a wide range of physical abilities. This promotes inclusivity and empowers individuals with varying levels of mobility impairments to independently control their wheelchairs.

Furthermore, gesture recognition interfaces allow for hands-free operation, freeing the user's hands for other tasks or activities. This can be particularly valuable in situations where users need to simultaneously manipulate objects or interact with their environment while operating the wheelchair (Sahoo et al., 2023). For example, individuals with limited upper-body strength can use gestures to control the wheelchair without the need for physical exertion. While gesture recognition interfaces offer significant potential, they also present some challenges. Variability in user gestures, lighting conditions, and occlusions can affect the accuracy and reliability of the recognition system. Robust computer vision algorithms and machine learning models are necessary to handle these challenges and ensure accurate gesture interpretation.

Gesture recognition interfaces offer a promising approach to human-robot interaction in smart robotic wheelchairs. They provide an intuitive, accessible, and hands-free means of controlling the wheelchair, enabling individuals with mobility impairments to operate their devices with greater ease and independence. As advancements in computer vision and machine learning continue to evolve, gesture recognition interfaces have the potential to enhance the user experience and improve the overall usability of smart robotic wheelchairs.

Voice command interfaces

Voice command interfaces are an increasingly prevalent technology in the field of human-robot interaction (HRI) for smart robotic wheelchairs. These interfaces allow users to control and interact with their wheelchairs through spoken commands, providing a natural and hands-free means of operation. Voice command interfaces utilize automatic speech recognition (ASR) technology to convert spoken words into actionable commands, enabling seamless communication between users and their wheelchairs.

The process of voice command recognition involves several stages. Firstly, the user speaks a command or instruction, which is captured by a microphone or voice input device. The recorded speech is then processed by ASR algorithms, which convert the audio signals into textual representations. Natural language understanding (NLU) techniques are applied to interpret the meaning and intent behind the recognized text. These algorithms analyze the command, extract relevant information, and map it to predefined actions or functionalities within the wheelchair's control system (Huq et al., 2022). Voice command interfaces offer several benefits in the context of smart robotic wheelchairs. Firstly, they provide a natural and intuitive mode of interaction, mimicking human-human communication. Users can express their commands and preferences using familiar language, reducing the learning curve and cognitive load associated with other control interfaces (Sahoo and Choudhury, 2022). This can be particularly advantageous for individuals with limited dexterity or motor control, as it eliminates the need for physical manipulation of control devices.

Moreover, voice command interfaces enhance accessibility, as they do not require physical contact or fine motor skills to operate. Individuals with limited hand function or mobility impairments can easily control their wheelchairs using voice commands, promoting inclusivity and independence. This feature is particularly valuable in situations where users may have difficulty operating traditional joystick-based interfaces or touchscreens. Additionally, voice command interfaces offer hands-free operation, freeing the user's hands for other tasks or activities. Users can control their wheelchairs while simultaneously manipulating objects, carrying items, or performing other daily activities. This flexibility improves user autonomy and allows for multitasking in various environments (Liu et al., 2021).

However, voice command interfaces also present challenges. Accurate speech recognition is a critical factor for successful operation. Variability in speech patterns, accents, background noise, and environmental conditions can impact the accuracy of recognition systems. Robust ASR and NLU algorithms are necessary to handle these challenges and ensure reliable and accurate command interpretation. Another consideration is the system's response time. Users expect immediate and accurate responses to their voice commands. Therefore, voice command interfaces should be designed to minimize latency and provide real-time feedback, allowing users to gauge the system's understanding and responsiveness. Voice command interfaces offer a promising approach to human-robot interaction in smart robotic wheelchairs. They provide a natural, hands-free, and accessible means of controlling the wheelchair, enabling individuals with mobility impairments to operate their devices with ease and independence. As advancements in ASR and NLU technologies continue to evolve, voice command interfaces have the potential to enhance the user experience, improve usability, and foster increased autonomy for users of smart robotic wheelchairs.

Brain-computer interfaces

Brain-computer interfaces (BCIs) represent an advanced and cutting-edge technology in the field of human-robot interaction (HRI) for smart robotic wheelchairs. BCIs establish a direct communication channel between the human brain and the wheelchair's control system, enabling individuals with severe mobility impairments to control their wheelchairs using neural signals (Masengo et al., 2023). This technology holds tremendous potential for enhancing independence and quality of life for individuals with limited or no motor function.

BCIs operate by capturing and interpreting the brain's electrical activity, typically using electroencephalography (EEG) or invasive implants. EEG-based BCIs use a cap or electrodes placed on the user's scalp to record electrical signals generated by the brain. These signals are then processed and decoded using advanced signal processing and machine learning algorithms. Invasive BCIs involve the implantation of electrodes directly into the brain tissue to capture neural activity with higher precision (Xu et al., 2019). The decoding algorithms of BCIs translate the recorded neural signals into actionable commands for the wheelchair. This requires sophisticated pattern recognition techniques to accurately identify the user's intended actions or movements based on the neural signals. Machine learning algorithms play a vital role in training the BCI system to recognize specific brain patterns associated with different commands. BCIs offer several advantages in the context of smart robotic wheelchairs. Firstly, they enable individuals with severe motor impairments, such as spinal cord injuries or neuromuscular disorders, to regain control and autonomy over their mobility. By bypassing the traditional pathways of motor control, BCIs provide an alternative communication channel that directly taps into the user's intentions.

Furthermore, BCIs offer a high level of precision and fine-grained control (Yenugula et al., 2023). Users can perform complex commands, such as navigating through tight spaces, turning, or stopping, with precise and nuanced control using their neural signals. This level of control is particularly important for tasks that require precise movements and spatial awareness.

Moreover, BCIs can provide a faster and more efficient means of communication compared to traditional control interfaces. Once the user becomes proficient in operating the BCI system, the translation from brain signals to wheelchair commands can occur rapidly and seamlessly, minimizing response time and allowing for real-time control (Belkacem et al., 2020). Brain-computer interfaces offer a groundbreaking approach to human-robot interaction in smart robotic wheelchairs. They provide individuals with severe motor impairments the ability to control their wheelchairs directly through their neural signals, offering unprecedented independence and mobility. Ongoing research and advancements in signal processing, machine learning, and neural decoding techniques hold the promise of further improving the accuracy, reliability, and usability of BCIs in the context of smart robotic wheelchairs.

Multimodal interaction strategies

Multimodal interaction strategies are a powerful approach in the field of human-robot interaction (HRI) for smart robotic wheelchairs. These strategies combine multiple modes of communication, such as speech, gestures, touch, and visual cues, to enhance the interaction between users and their wheelchairs. By incorporating multiple modalities, multimodal interaction strategies aim to provide more robust, flexible, and natural means of communication and control. The combination of different modalities allows users to leverage their preferred modes of communication and interact with the wheelchair in a more intuitive and personalized manner. For example, users can simultaneously use speech commands, gestures, and touch inputs to convey their intentions and preferences to the wheelchair (berg and Lu, 2020). This multimodal approach accommodates individual differences in user capabilities, preferences, and environmental contexts, providing a more inclusive and adaptable interaction framework.

Multimodal interaction strategies often utilize machine learning algorithms to process and interpret data from multiple modalities. These algorithms can analyze and integrate information from different sources to generate a comprehensive understanding of the user's intent. For example, speech recognition algorithms can be combined with gesture recognition and visual tracking techniques to create a multimodal fusion approach that enhances the accuracy and reliability of user commands. The benefits of multimodal interaction strategies in smart robotic wheelchairs are manifold. Firstly, they enhance the naturalness and flexibility of communication. By integrating multiple modes, users can express themselves using a combination of verbal cues, physical gestures, and visual references, mirroring natural human-human communication. This promotes a more intuitive and engaging interaction experience (Yenugula et al., 2024).

Secondly, multimodal interaction allows for redundancy and error correction. In situations where one modality may be ambiguous or noisy, other modalities can serve as backup or provide additional context. For instance, if a speech command is unclear, the wheelchair can rely on gestures or visual cues to disambiguate the user's intention. This redundancy improves robustness and reduces the likelihood of misinterpretation. Furthermore, multimodal interaction can enhance accessibility and inclusivity. By offering multiple means of interaction, individuals with diverse abilities and preferences can engage with the wheelchair more effectively. Users with speech impairments may rely on gestures or touch inputs, while those with limited mobility may utilize voice commands and visual cues (Alonso et al., 2021). This flexibility enables a broader range of users to interact with the wheelchair comfortably.

Multimodal interaction strategies offer a powerful framework for human-robot interaction in smart robotic wheelchairs. By combining multiple modalities, these strategies enhance naturalness, flexibility, robustness, and inclusivity of communication and control. Ongoing research in multimodal fusion, machine learning, and sensor technologies will continue to advance the effectiveness and usability of multimodal interaction strategies, further improving the interaction experience and empowering individuals with mobility impairments to control their wheelchairs with greater ease and independence.

User Experience Considerations

User experience considerations are paramount in the design of robotic wheelchairs, focusing on ensuring optimal usability, comfort, safety, personalization, integration, and long-term user satisfaction. By prioritizing intuitive control interfaces, comfortable seating systems, reliable obstacle detection, and collision avoidance, as well as offering customization options and seamless integration into users' environments, robotic wheelchairs can enhance the overall user experience. These considerations aim to empower individuals with mobility impairments, promoting their independence, mobility, and well-being.

Usability evaluation methods

Usability evaluation methods are essential in assessing the user experience and effectiveness of robotic wheelchairs. These methods involve various techniques and approaches that provide valuable insights into the usability, efficiency, and user satisfaction with the wheelchair's design and functionality. Here, we discuss some commonly used usability evaluation methods in detail.

- User Testing: User testing involves observing and collecting feedback from users as they interact with the robotic wheelchair. This can be done through structured tasks or scenarios that simulate real-world usage (Di et al., 2013). Observations, interviews, and questionnaires are used to gather qualitative and quantitative data on aspects such as ease of use, task completion time, and user satisfaction. User testing provides direct insights into the strengths and weaknesses of the wheelchair's design and usability from the user's perspective.
- Expert Evaluation: Expert evaluation involves usability experts or domain specialists assessing the wheelchair's design and functionality based on established usability heuristics or guidelines (Zahabi et al., 2022). These experts evaluate the system using their expertise and experience to identify potential usability issues, cognitive load, and interaction complexities. Expert evaluation provides valuable insights into design flaws and areas for improvement, complementing user feedback.
- Cognitive Walkthrough: Cognitive walkthroughs focus on the user's cognitive processes and decision-making while using the robotic wheelchair. Evaluators analyze each step or interaction in a task and assess whether the user's goals, information requirements, and actions align with the wheelchair's design (Czaja and Ceruso, 2022). This method helps identify potential cognitive challenges, information gaps, and usability obstacles that may impede the user's successful completion of tasks.
- Task Analysis: Task analysis involves breaking down complex tasks into smaller subtasks or steps to understand the cognitive and physical demands placed on the user. By examining the sequence of actions required to accomplish tasks, task analysis identifies potential bottlenecks, redundancies, or gaps in the wheelchair's workflow. This method helps optimize task design and streamline user interactions, ultimately enhancing usability and efficiency.

These usability evaluation methods, when used individually or in combination, provide a comprehensive understanding of the wheelchair's usability, user satisfaction, and areas for improvement. By incorporating these evaluation methods into the design and development process, robotic wheelchair designers can iteratively refine and optimize the system to meet the specific needs and preferences of users, ultimately enhancing the overall user experience and promoting user independence and mobility.

Learnability and efficiency

Learnability and efficiency are key considerations in the design and evaluation of robotic wheelchairs' user experience. Learnability refers to the ease with which users can learn to operate the wheelchair effectively, while efficiency focuses on the speed and accuracy with which users can accomplish tasks using the wheelchair. Both factors are crucial in ensuring that users can quickly adapt to the wheelchair's functionality and interact with it in a productive and efficient manner.

Learnability can be enhanced through several design considerations. First, the user interface should be intuitive and provide clear feedback to guide users in understanding how to control the wheelchair. Clear and concise instructions, visual cues, and user-friendly interfaces help users quickly grasp the necessary actions and operations. The system should be designed with simplicity in mind, avoiding unnecessary complexity or overwhelming options that could hinder the learning process. Training and education also play a vital role in promoting learnability. Providing comprehensive user manuals, tutorials, or interactive training sessions can familiarize users with the wheelchair's features, controls, and functionalities (WHO, 2023). In addition, ongoing support, such as accessible helplines or online resources, can be valuable for users to address any questions or difficulties they may encounter during their initial learning phase.

Efficiency, on the other hand, focuses on optimizing the speed and accuracy of user interactions with the wheelchair. Efficient wheelchair design entails minimizing the number of steps or actions required to complete tasks, reducing cognitive load, and streamlining user workflows. This can be achieved by leveraging automation, intelligent algorithms, and adaptive control systems that anticipate user needs and proactively assist with task completion (Gowran et al., 2022). By prioritizing learnability and efficiency, designers of robotic wheelchairs can create systems that enable users to quickly grasp the wheelchair's operation, maximize their productivity, and achieve their desired tasks with speed and accuracy. This ensures a positive user experience, empowers users with greater independence, and facilitates their integration into various environments with enhanced mobility.

User satisfaction assessment

User satisfaction assessment is a critical aspect of evaluating the user experience of robotic wheelchairs. It involves gathering feedback from users to understand their perceptions, preferences, and overall satisfaction with the wheelchair's design, functionality, and performance (Bouffard et al., 2022). Assessing user satisfaction helps identify strengths, weaknesses, and areas for improvement, allowing designers to tailor the wheelchair's features and interactions to meet users' needs and expectations. There are various methods and techniques for assessing user satisfaction in the context of robotic wheelchairs:

- Surveys and Questionnaires: Surveys and questionnaires provide a structured approach to collect user feedback. Standardized scales, such as the System Usability Scale (SUS) or the Technology Acceptance Model (TAM), can be employed to measure user satisfaction, perceived ease of use, and perceived usefulness. Open-ended questions allow users to provide detailed feedback, suggestions, and specific areas of concern or satisfaction.
- Interviews: Interviews offer an opportunity for in-depth discussions with users, allowing researchers to delve into their experiences, perceptions, and preferences regarding the wheelchair. Semi-structured or structured interviews can be conducted to explore specific aspects of user satisfaction, usability challenges, or areas where the wheelchair excels. These interviews provide rich qualitative insights and uncover nuanced perspectives.
- Usability Testing: Usability testing involves users performing specific tasks or scenarios using the robotic wheelchair while researchers observe and collect data. User actions, task completion time, errors, and subjective feedback are recorded to assess usability and satisfaction. This method provides both quantitative and qualitative data, offering insights into the effectiveness and efficiency of the wheelchair in meeting user needs.
- Post-use Evaluation: After users have interacted with the robotic wheelchair for a certain period, post-use evaluation methods can be employed to capture long-term user satisfaction. These methods may include follow-up surveys, interviews, or focus groups to gather feedback on user experiences over an extended duration. Longitudinal assessments enable the identification of evolving needs, challenges, and satisfaction levels as users gain familiarity and experience with the wheelchair.

- User Experience Metrics: User experience metrics, such as the Net Promoter Score (NPS) or the Customer Satisfaction Score (CSAT), provide quantitative measures of overall user satisfaction and loyalty. These metrics allow for benchmarking and comparison across different iterations or versions of the wheelchair, enabling designers to track improvements over time.

By employing a combination of these assessment methods, researchers and designers can gain comprehensive insights into user satisfaction with robotic wheelchairs. This information can be used to identify usability issues, areas of improvement, and opportunities to enhance user satisfaction. Regular user satisfaction assessments and continuous user involvement throughout the design process facilitate iterative improvements, leading to the development of more user-centered and satisfying robotic wheelchairs.

User-centered design principles

User-centered design (UCD) principles are fundamental guidelines that focus on designing products, such as robotic wheelchairs, with the needs, preferences, and capabilities of users at the forefront (Zablocki et al., 2022). UCD aims to create intuitive, usable, and satisfying experiences for individuals with mobility impairments, placing them at the center of the design process. Here, we explore key UCD principles in detail.

- User Involvement: UCD emphasizes active involvement of users throughout the design process. Engaging users in activities such as interviews, observations, and usability testing allows designers to gain insights into their needs, challenges, and aspirations. User feedback and preferences guide the decision-making process, ensuring that the wheelchair's design and features align with the users' goals and expectations.
- User Research: User research involves conducting thorough investigations to understand the target users, their characteristics, contexts, and unique requirements. This research encompasses factors such as physical abilities, cognitive capabilities, lifestyle, and environmental considerations. By gaining a deep understanding of the user base, designers can create solutions that address specific needs and enhance user satisfaction.
- Iterative Design: UCD embraces an iterative approach to design, where solutions are refined through multiple cycles of prototyping, evaluation, and user feedback. Each iteration builds upon previous insights, allowing designers to address usability issues, refine features, and enhance the overall user experience. This iterative process ensures that the final product is well-adapted to users' needs and preferences.
- Accessibility and Inclusivity: UCD emphasizes designing for accessibility and inclusivity, considering the diverse range of users with varying abilities and disabilities. Designers strive to remove barriers and provide equitable access to all users. This involves ensuring physical accessibility, accommodating different cognitive capabilities, and addressing sensory or motor impairments. Design choices such as adjustable seating, multiple control options, and customizable interfaces promote inclusivity.
- Clear and Consistent Interfaces: UCD emphasizes the importance of clear and consistent interfaces that facilitate ease of use and reduce cognitive load. Designers strive to create intuitive control layouts, provide feedback through visual or auditory cues, and use consistent icons or symbols to convey information. By minimizing complexity and providing a familiar and predictable interaction framework, users can quickly understand and navigate the wheelchair's features.
- Feedback and Error Handling: UCD emphasizes the provision of timely and informative feedback to users. The wheelchair should provide clear indications of system status, acknowledge user commands, and communicate error messages effectively. Meaningful feedback helps users understand the system's behavior, recover from errors, and maintain a sense of control and confidence.

By embracing these UCD principles, designers can create robotic wheelchairs that are intuitive, usable, and satisfying for individuals with mobility impairments. UCD promotes an empathetic and holistic approach to design, ensuring that the wheelchair meets the specific needs, preferences, and aspirations of its users, ultimately enhancing their independence, mobility, and overall well-being.

Safety and Trust in Human-Robot Interaction

Safety and trust are critical factors in human-robot interaction (HRI). In HRI, safety refers to the assurance that the robot operates without causing harm to users or its surroundings. It involves robust obstacle detection, collision avoidance, and fail-safe mechanisms to prevent accidents and injuries (Vasconez et al., 2019). Trust, on the other hand, encompasses the user's confidence and belief in the robot's reliability, capabilities, and intentions. Establishing safety and trust in HRI is crucial to ensure user confidence, promote effective collaboration, and enable users to rely on robots for assistance and support.

Collision avoidance and risk mitigation

Collision avoidance and risk mitigation are vital features in smart robotic wheelchairs that aim to ensure user safety and prevent accidents or collisions in various environments. These features leverage advanced sensing technologies, intelligent algorithms, and adaptive control systems to detect and respond to potential obstacles or hazards. Smart robotic wheelchairs employ various sensors, such as proximity sensors, cameras, or lidar, to continuously scan the surrounding environment. These sensors provide real-time data about the wheelchair's surroundings, detecting obstacles, objects, or people in its path. By accurately perceiving the environment, the wheelchair can make informed decisions and take appropriate actions to avoid potential collisions.

The collision avoidance algorithms in smart robotic wheelchairs analyze the sensor data and assess the risk levels associated with detected obstacles. These algorithms calculate the proximity, speed, and trajectory of obstacles relative to the wheelchair, allowing the wheelchair to predict potential collisions and determine the most appropriate course of action. Depending on the situation, the wheelchair may adjust its speed, direction, or halt completely to prevent collisions.

Risk mitigation strategies in smart robotic wheelchairs involve proactive measures to minimize the likelihood or impact of potential accidents. These strategies may include adjusting the wheelchair's speed or acceleration based on the detected risk level, activating additional safety features, or providing timely warnings to the user about potential hazards. By dynamically adapting its behavior to the risk levels, the wheelchair can prioritize user safety and mitigate potential dangers. Continuous research and development in collision avoidance and risk mitigation for smart robotic wheelchairs aim to improve the accuracy, reliability, and effectiveness of these features. Advancements in sensing technologies, machine learning algorithms, and real-time decision-making allow for more robust and adaptive collision avoidance systems, ensuring safer and more secure interactions between users and smart robotic wheelchairs.

Trust-building mechanisms

Trust-building mechanisms in smart robotic wheelchairs are designed to foster a sense of reliability, predictability, and confidence in the interaction between users and the robotic system. These mechanisms aim to establish a trusting relationship between the user and the wheelchair, ensuring smooth and effective collaboration. Several factors contribute to building trust in smart robotic wheelchairs.

- Reliable and Consistent Performance: The wheelchair should consistently demonstrate reliable and accurate performance in its actions and responses. Users should have confidence that the wheelchair will operate as intended, follow commands accurately, and navigate safely. By delivering consistent and predictable performance, the wheelchair builds trust by meeting user expectations and reducing uncertainty.
- Transparent Communication: Transparent communication is crucial in building trust. The wheelchair should provide clear and understandable feedback to the user, conveying its intentions, actions, and status. This includes visual or auditory cues that indicate the wheelchair's current state, planned movements, and any detected obstacles or risks. Transparent communication helps users understand and anticipate the wheelchair's behavior, enhancing trust and facilitating effective collaboration.
- Explainable Decision-Making: Smart robotic wheelchairs often employ complex algorithms and decision-making processes. To build trust, it is important that these decisions are explainable to the user. Users should be able to understand why the wheelchair made a particular choice or took a specific action. Providing explanations or

visualizing the decision-making process can help users feel more involved and informed, promoting trust in the system's capabilities.

- User Control and Override: Allowing users to have a degree of control and override capability enhances trust. Users should feel that they have the ability to intervene, modify, or correct the wheelchair's actions when needed. This can be achieved through intuitive and accessible control interfaces, emergency stop buttons, or manual control options. User control and override mechanisms provide users with a sense of agency and contribute to their trust in the wheelchair's operation.

By incorporating these trust-building mechanisms, smart robotic wheelchairs can create a positive user experience and foster a sense of reliability, transparency, and user confidence. Building trust is essential to maximize user acceptance, collaboration, and satisfaction, enabling individuals with mobility impairments to embrace and benefit from the capabilities of smart robotic wheelchairs.

Ethical considerations and privacy protection

Ethical considerations and privacy protection are crucial aspects to address in the development and deployment of smart robotic wheelchairs. These considerations aim to ensure the responsible use of technology, protect user privacy, and uphold ethical principles in the interaction between users and the robotic system.

- Informed Consent: Obtaining informed consent is essential before deploying smart robotic wheelchairs. Users should be fully informed about the capabilities, limitations, and potential risks associated with the technology. They should have a clear understanding of how their personal data will be collected, used, and protected. Informed consent allows users to make informed decisions and exercise control over their participation in the robotic wheelchair program.
- Privacy Protection: Protecting user privacy is paramount. Smart robotic wheelchairs may collect various types of personal data, such as location information, health data, or user preferences. It is important to implement robust data protection measures to ensure the confidentiality, integrity, and controlled access of user data. Anonymization or pseudonymization techniques can be employed to minimize the risk of re-identification. Data encryption, secure data storage, and access controls help safeguard user privacy.
- Data Minimization: Adhering to the principle of data minimization involves collecting only the necessary data required for the functioning of the smart robotic wheelchair. Unnecessary or excessive data collection should be avoided to minimize privacy risks. By limiting data collection to essential information, the risk of potential data breaches or unauthorized access is reduced.
- Transparency: Ensuring transparency in the operation and use of smart robotic wheelchairs is crucial. Users should have clear visibility into how the wheelchair operates, the data it collects, and how that data is utilized. Transparent communication about the purpose, capabilities, and potential impact of the technology helps users make informed decisions and promotes trust in the system.

By incorporating these ethical considerations and privacy protection measures, smart robotic wheelchairs can operate in a responsible and user-centric manner. Respecting user privacy, promoting transparency, and upholding ethical principles foster trust, enhance user acceptance, and ensure the long-term viability and benefits of smart robotic wheelchairs in improving the lives of individuals with mobility impairments.

Conclusion

This review paper has explored the fascinating field of human-robot interaction (HRI) and user experience in the context of smart robotic wheelchairs. Through an in-depth examination of various aspects, including technology advancements, personalized control, interface design, user satisfaction, and ethical considerations, we have gained valuable insights into the current state and future directions of this rapidly evolving field.

The research gap and novelty in this area lie in the need for further exploration and development of personalized and adaptive features that enhance the user experience and promote independence, safety, and comfort. While significant progress has been made in technology advancements, there is still room for improvement in areas such as navigation algorithms, gesture recognition interfaces, voice command interfaces, and brain-computer interfaces. Additionally, considerations for user satisfaction, usability evaluation, learnability, efficiency, and user-centered design principles have been highlighted as critical factors in the successful design and implementation of smart robotic wheelchairs. Furthermore, the review has shed light on the importance of trust-building mechanisms, safety, and privacy protection in human-robot interaction. Trust, transparency, and user empowerment are fundamental for fostering acceptance, collaboration, and positive user experiences. Ethical considerations, including informed consent, privacy protection, and ethical decision-making, must be at the forefront of the development and deployment of smart robotic wheelchairs to ensure responsible and ethical use of this technology.

Practical Implication

The practical implications of this review paper on human-robot interaction (HRI) and user experience in smart robotic wheelchairs are significant for various stakeholders involved in the design, development, and deployment of these assistive devices. The following practical implications can be drawn from the findings:

- Design Guidelines: The review highlights the importance of user-centered design principles and customization in smart robotic wheelchair development. Designers and engineers can leverage these guidelines to create interfaces, control systems, and adaptive behaviors that prioritize user needs, preferences, and capabilities. By incorporating user feedback throughout the design process, practitioners can ensure that the wheelchair's features and interactions align with user expectations, enhancing overall user experience.
- Technology Advancements: The paper emphasizes the need for ongoing technology advancements in areas such as robotics, sensors, artificial intelligence, and machine learning. Practitioners can stay updated with the latest advancements and innovations to enhance the capabilities and performance of smart robotic wheelchairs. Implementing advanced navigation algorithms, gesture recognition interfaces, voice command interfaces, and brain-computer interfaces can improve the wheelchair's responsiveness, adaptability, and ease of use.
- Safety and Trust: Safety considerations and trust-building mechanisms are crucial practical implications highlighted in the paper. Practitioners should prioritize safety features such as collision avoidance, risk mitigation, and fail-safe mechanisms in smart robotic wheelchair designs. Implementing transparent communication, user control, and explainable decision-making can foster trust between users and the robotic system. By addressing ethical considerations and privacy protection, practitioners can ensure responsible and trustworthy deployment of smart robotic wheelchairs.

These practical implications provide valuable guidance for practitioners and stakeholders in the field of smart robotic wheelchairs. By implementing these recommendations, practitioners can enhance the user experience, improve usability, prioritize safety, and foster trust in the interaction between users and smart robotic wheelchairs.

Limitation

While this review paper provides valuable insights into human-robot interaction (HRI) and user experience in smart robotic wheelchairs, it is important to acknowledge certain limitations:

- Knowledge Cutoff: The review paper's limitations are tied to the knowledge cutoff date, which is the point at which the paper's literature review ends. As an AI language model, my knowledge cutoff is September 2021. Therefore, newer research, technological advancements, or emerging trends beyond this date may not be included in the paper. It is advisable for readers to supplement their understanding by referring to more recent studies and literature.
- Individual Variability: HRI and user experience are highly individualized and subjective. The review paper provides a general overview and discusses common trends and considerations. However, individual user preferences, abilities, and contexts can significantly influence their

experience with smart robotic wheelchairs. It is important to recognize that user experiences may vary, and there may not be a one-size-fits-all solution for every user.

- Lack of Empirical Studies: While the review paper may draw from empirical studies and existing research, the paper itself may not present new empirical findings. It relies on synthesizing and summarizing existing knowledge and research. Therefore, the conclusions and implications drawn from the review are based on the available literature, and further empirical studies are necessary to validate and expand upon the findings.

Despite these limitations, this review paper offers a comprehensive overview of the current state of research in HRI and user experience in smart robotic wheelchairs. It provides a foundation for further exploration, empirical studies, and advancements in the field, guiding future research and development efforts to improve the usability, safety, and overall user satisfaction with these assistive technologies.

Future Scope

The review paper on human-robot interaction (HRI) and user experience in smart robotic wheelchairs opens up several avenues for future research and development. The following future scope can be considered:

- Advanced Sensing Technologies: Future research can focus on integrating advanced sensing technologies into smart robotic wheelchairs. This includes the use of more sophisticated sensors such as 3D cameras, depth sensors, or wearable sensors to improve obstacle detection, object recognition, and environment perception. By enhancing the perception capabilities of the wheelchair, it can navigate complex environments more effectively and ensure user safety.
- Multimodal Interaction: Further exploration of multimodal interaction strategies can be pursued. Combining different modes of communication, such as gesture recognition, voice commands, haptic feedback, or brain-computer interfaces, can enable more intuitive and natural interactions between users and smart robotic wheelchairs. Future research can delve into the development of robust multimodal interfaces that adapt to individual user preferences and abilities.
- Social and Emotional Interaction: Exploring the integration of social and emotional intelligence in smart robotic wheelchairs can be a fascinating avenue for future research. This involves developing algorithms that enable the wheelchair to recognize and respond to user emotions, provide social cues, and engage in more human-like interactions. By incorporating social and emotional aspects, the wheelchair can foster a sense of companionship and support for users.

By pursuing these future research directions, the field of HRI and user experience in smart robotic wheelchairs can continue to evolve, leading to more advanced, user-centric, and inclusive assistive technologies. The future scope encompasses advancements in sensing technologies, multimodal interaction, personalized control, social and emotional interaction, context-aware adaptability, long-term user studies, and ethical considerations, ultimately contributing to the improvement of smart robotic wheelchairs and the well-being of individuals with mobility impairments.

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Conflict of interest

There are no conflicts of interest to disclose, according to the author(s).

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Author Contribution

The idea and design of the study were contributed to by S. K. Sahoo and B. B. Choudhury. S. K. Sahoo wrote the manuscript and helped with the material processing and collecting. The document was modified by Dr. B.B. Choudhury.

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