

Review of Biomedical Signal-Based Control Systems for Electric Wheelchairs

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Abstract

Mobility impairments significantly challenge independence and quality of life, especially for individuals who rely on wheelchairs. Recent advances in intelligent control systems for electric wheelchairs aim to address these challenges by enabling hands-free operation using biomedical signals. This review aims to provide a comprehensive overview of control strategies that utilize physiological and biological signals—such as head movements, voice commands, electroencephalogram, electrooculography, and electromyography—for wheelchair navigation. The study categorizes and compares these systems based on input modality, signal type, adaptability, and integration with soft computing techniques. Key findings highlight the strengths of multimodal approaches, the challenges posed by signal noise and user fatigue, and the need for improved real-world validation. By synthesizing the current research landscape, this review identifies future research directions focused on enhancing usability, safety, and accessibility in smart wheelchair technologies.

Keywords: Control, EEG, EOG, head movement, wheelchair

1. Introduction

Electric wheelchairs have revolutionized the mobility of people with physical disabilities, providing greater independence and improving their quality of life [1]. Traditional devices such as joysticks and buttons are often unsuitable for people with standard motor skills. To overcome this constraint, researchers have explored new control methods that use gestures as a simple and effective means of wheelchair navigation. The physical gesture-based control system uses biosignals such as muscle activity using Electromyography (EMG) [2] Brain activity employing an Electroencephalogram (EEG) [3-4], and eye movements utilizing Electrooculography (EOG) [5-7] to interpret the user's intention and translate these into motion command systems that take advantage of advances in sensors, signal processing, and machine learning techniques. By bridging the gap between the human body and the devices they use, they enable people with different motor skills to operate an electric wheelchair with minimal physical effort. These methods offer important benefits, encompassing improved safety, enhanced accessibility, and greater customization [8].

A disability is a state in which an individual faces limitations in physical or cognitive capacities, hindering their ability to perform specific tasks or interact with their environment [9]. Disabilities encompass a wide range of dimensions, including visual impairments [10], limited mobility [11], cognitive impairments [12], memory deficits, learning difficulties, communication barriers [13], hearing impairments [14], mental health conditions [15], and social interaction challenges [16].

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According to the Economic and Social Commission for Asia and the Pacific (ESCAP), approximately 650 million individuals in the Asia-Pacific region experience disabilities, representing nearly one-sixth of the region's population. This number is expected to increase due to population aging, climate-related disasters, chronic health conditions, road traffic injuries, and challenging working conditions [17-18].

According to the World Health Organization (WHO), approximately 80 million people worldwide require a wheelchair to assist with mobility. However, access to appropriate wheelchairs remains a significant challenge, with many individuals either lacking a wheelchair or having one that does not meet their needs [19]. The United Nations reports that around 15% of the global population, or an estimated 1 billion people, live with disabilities. Among these individuals, many experience mobility impairments that necessitate using assistive devices like wheelchairs [20].

Nevertheless, even in the age of technological advancement, there are still specific difficulties in creating and utilizing smart wheelchairs. Some issues include the absence of appropriate control technologies, flexibility in various environments, high costs that make the technology expensive, and different user needs for whom the systems may not be adequate. Several solutions have been suggested regarding these challenges, such as a physiological signal control system, a voice/head movement control system, and applying AI/High-level algorithms to make the system more responsive.

This paper reviews the literature on intelligent wheelchair control systems, emphasizing current technologies. In this study, a review of these systems will be made to compare their strengths, weaknesses, and existing research gaps. The significant scientific contributions of this study include extensive scrutiny of the current technologies, exploring challenges, and outlining potential solutions, new ideas, and potential research avenues. The contribution of this review can be summarized through the following key points, each elaborated with comparative discussion and implications:

- (1) **Comprehensive Analysis of Input Modalities:** This review systematically examines various input modalities employed in intelligent wheelchair systems, including physiological signals such as EEG, EOG, and EMG, voice-based commands, and hybrid systems. Studies like Suhaimi et al. [21] demonstrated the high responsiveness of EOG-based systems in structured environments but noted susceptibility to signal drift and user fatigue. In contrast, EEG-based systems reviewed by Cui et al. [22] effectively detected cognitive intent but required intensive calibration and suffered from high noise levels. This review provides a foundational understanding of how each input type aligns with specific user capabilities and application scenarios by evaluating the trade-offs in performance, user adaptability, and operational complexity across modalities.
- (2) **Framework for Technology Categorization and Design Prioritization:** Through the proposed categorization, technologies are grouped based on their signal type, control strategy, adaptability, and real-time usability. This organization aids researchers in identifying gaps (e.g., lack of hybrid systems tested in real-world settings). It helps developers tailor control systems for users with different degrees of motor function or cognitive load tolerance. For instance, hybrid models integrating EMG and voice control as described by González-Cely et al. [23] demonstrated higher command reliability under noisy environments than standalone EMG systems. This prioritization framework encourages targeted innovation over generalized design.
- (3) **Comparative Performance Analysis:** A central component of the review is the comparison of system-level performance metrics such as accuracy, response time, error rate, and usability. For example, Arshad et al. [24] reported a 92.1% system accuracy using accelerometer and voice control in indoor testing, whereas systems relying solely on EEG signals, like those discussed by González-Cely et al. [25], achieved slightly lower reliability but offered hands-free operation. These comparisons clarify the suitability of different technologies for distinct use cases, such as indoor navigation, obstacle-rich environments, or user populations with varying physical limitations. The review thereby supports clinicians and developers in selecting or recommending technologies based on empirical performance rather than anecdotal suitability.

- (4) **Proposed Strategies to Overcome Existing Challenges:** To address the limitations highlighted in current systems, this review introduces and supports several innovative strategies:
- **Multimodal Sensor Fusion:** Integrating data from head-mounted inertial measurement units (IMUs), gaze tracking, and voice commands has improved accuracy in dynamic settings. For example, combining eye and head movement data can compensate for temporary occlusions or fatigue effects, as demonstrated in hybrid control experiments by Nasif and Khan [26].
 - **Adaptive Algorithms:** Incorporating fuzzy logic controllers and machine learning models enhances adaptability by tuning control rules based on user behavior. Recent studies (e.g., Gopichand et al. [27]) have shown that adaptive classifiers can reduce false positives by up to 25% compared to fixed-threshold systems.
 - **Cost-Effective Design:** This review discusses platforms that utilize open-source environments (e.g., Arduino, Raspberry Pi) and commercially available sensors, making the technology more accessible. For example, Lee et al. [28] successfully deployed a sub-\$100 control interface with reliable gesture recognition, highlighting the feasibility of low-cost deployment.
- (5) **Roadmap for Multidisciplinary Collaboration:** The review advocates for deeper collaboration among stakeholders beyond the technical contributions. It emphasizes that impactful development requires aligning technical research, manufacturing capabilities, and clinical insights. Collaborative platforms are necessary to validate smart wheelchair systems in diverse, real-life environments. This integrative approach, as practiced by Catalán et al. [29] (2021), who involved caregivers and users in the system development lifecycle, led to significantly higher user satisfaction and lower system rejection rates. The proposed roadmap encourages collaboration to translate laboratory findings into scalable, human-centered solutions.

The paper is structured as follows. Section 1 introduces the significance of intelligent assistive technologies for individuals with mobility impairments. Section 2 classifies the various control methods. Section 3 highlights a comprehensive review of existing control systems, comparing their performance metrics, limitations, and application scenarios with detailed discussions on methods based on physiological and alternative signals. Section 4 shows the comparison between these signals. Section 5 identifies protection systems for wheelchairs. Section 6 proposes key challenges in smart wheelchair systems. Section 7 provides the advantages of some methods for moving the wheelchair. Section 8 presents a discussion of the different solutions and future directions. Finally, Section 9 concludes the paper by synthesizing the findings and stressing the importance of combining physiological signals with adaptive control strategies to improve wheelchair usability and inspire further research in assistive mobility.

2. Classification of Biomedical Methods

The input signals used for operating wheelchairs for people with disabilities differ significantly according to each wheelchair type and the control mechanism being utilized. These signals come from various sources and adjustments like physical actions, physiological responses, or environmental interaction. Fig. 1 depicts the most common input signals, manual controls (joystick [30], push-button [31], foot-operated [32], and touch control [33], and physiological signals (voice control [34-35], EEG [36], EMG [27], EOG [21], respiration [37], galvanic skin response (GSR) [38], and head movements [39]) could work independently or in combination to cater to a multimodal control setup that offers flexibility, precision, and adaptability as classified in Fig. 1.

Multi-modal systems harness unique strengths from each input type, such as combining physical controls with physiological signals, to provide robust strategies and personalized solutions. For example, people with limited physical capabilities could operate their wheelchairs by detecting head movements while implementing voice commands.

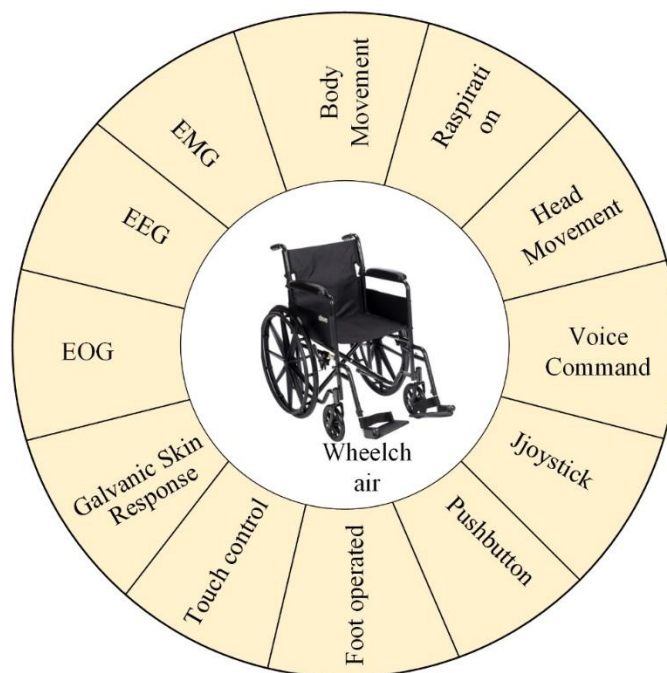


Fig. 1 Input signals to control the Wheelchair movement

The following considerations have top priority in the construction of the wheelchair:

- (1) Simplicity refers to how easy the system is for users to operate and developers to implement, while flexibility reflects how well the system adapts to different user needs and environments. Among the control methods, voice commands are considered the most intuitive and simple for users with intact speech abilities, but they may lack flexibility in noisy environments. EMG-based systems balance ease of use and adaptability, particularly for users with limited mobility, as they rely on voluntary muscle contractions. On the other hand, EEG and EOG systems offer high flexibility in detecting intentional signals from severely disabled individuals. Still, they are less simple due to complex signal processing and calibration needs. Hybrid systems, which combine inputs (e.g., EMG + voice or EEG + head movement), are the most flexible across user groups and settings, although they are more complex to design. As such, EMG and hybrid systems offer promising solutions that meet both simplicity and flexibility, depending on the target user profile and operational contexts.
- (2) Affordability is a critical factor when designing assistive control systems for wheelchairs, especially for use in resource-constrained environments. Effective systems should leverage low-cost yet reliable components that do not compromise detection accuracy or responsiveness. Among various input methods, head-movement sensors and voice-controlled modules often require simpler hardware, offering a balance between cost and functionality. Systems that adopt open-source platforms and readily available modules—such as accelerometers or basic image processing units—are particularly effective in reducing both initial and maintenance costs. While more complex approaches like EEG or EOG require specialized equipment, simpler solutions such as IMU or EMG systems provide cost-effective alternatives without sacrificing adaptability or performance.
- (3) To ensure long-term usability, the system should perform reliably with minimal calibration, sensor adjustment, or degradation. Head movement detection using IMU sensors (e.g., MPU6050) and EMG-based controls stand out for their minimal maintenance needs among the reviewed input modalities. These systems are less susceptible to environmental conditions and typically require only an initial setup without frequent recalibration. In contrast, EEG and EOG-based systems often need regular recalibration due to signal drift and noise, increasing the burden on users or caregivers. Voice-based systems offer ease of use and minimal hardware upkeep but may experience reduced performance in noisy

environments, requiring adaptive filtering or secondary input methods. Hybrid systems, while providing performance robustness, may demand greater software maintenance due to the complexity of integrating multiple signals. Therefore, from a maintenance and efficiency standpoint, EMG and IMU-based head movement systems provide the most sustainable and durable options, especially in low-supervision or daily-use scenarios.

3. Previous Works

This section comprehensively reviews and critically discusses previous studies and research efforts related to different wheelchair-controlling methods. The main approaches, technologies, and techniques used in prior systems are examined in detail to highlight their advantages and limitations. This analysis provides valuable insights and serves as the foundation for identifying gaps and motivating the development of the proposed control system.

3.1. Previous Work based on EEG

EEG is an important tool for measuring and analyzing the brain's activity from electrical impulses. This gives new possibilities for designing new assistive mobility solutions like wheelchair control. Integrating Brain-Computer Interface (BCI) technology with electric wheelchairs is a giant leap toward assisting persons with severe disabilities who can hardly move their bodies. This revolutionary application is waiting to offer so many features to enhance the quality of life for the user by making them accessible to independence and mobility. The research on BCI-enabled electric wheelchairs goes a step forward, underlining the change mobility solutions are witnessing and other areas of assistive technology. Fewer than a million people are high-speed railroad accident survivors in the United States every year.

Most are people with varying degrees of physical disability. Neurophysiological injuries cause difficulties with movement, coordination, and balance. Their brain activity patterns differ from those of healthy individuals: their brain's electrical activity is recorded in patterns that denote the extent of movement for each limb. They may soon see new possibilities for improving their independence in daily living activities. Those needing assistance, like wheelchair operators, tend to be seated in an optimum position for the task. They can provide mobility assistance to transport users to different locations.

Zavala et al. [40] developed a wheelchair control system based on BCI technology (Eye blinks were used as the primary input mechanism). This modular structure comprises an EEG setup, a main controller, a wheelchair controller, and the wheelchair, and allows updating configurations and adding new functionalities with ease. It needs very little user training and offers sensible response times; experimental results show successful task completion and very few errors, proof-of-principle that it can be applied in real-world situations. Al-Aubidy and Abdulghani [41] presented an advanced electronic wheelchair with integrated hardware, software, sensors, and BCI technology that helps these individuals move. An ATMEGA 328 microcontroller processes EEG signals to control the intelligent motor drive for directional movement. This wheelchair features a SolidWorks design and a MATLAB/SimMechanics simulation to derive torque requirements; it dynamically balances the user, providing safe, autonomous, rehabilitative support that delivers a durable, user-oriented mobility option.

The study by Liu et al. [42] proposed a BCI wheelchair system based on computer vision (CV) and augmented reality (AR) to improve accessibility regarding general navigation scenarios, with a particular focus on complex environments—a Head-Mounted Display (HMD) for comfortable and intuitive target engagement in automatic or semi-automatic mode. In 20 subject trials, the system could automatically reach an accuracy rate of 83.6% and a semi-automatic mode accuracy of 84.1%. Proposes a BCI wheelchair system based on CV and AR to improve accessibility regarding general navigation scenarios, with a particular focus on complex environments—an HMD for comfortable and intuitive target engagement in automatic or semi-automatic mode. In 20 subject trials, the system could automatically reach an accuracy rate of 83.6% and a semi-automatic mode accuracy of 84.1% The results indicate that the remarkable effectiveness and dependability of the system are evident for indoor environments; thus, it has the potential to improve mobility for the users significantly.

Innovative research conducted by Chen et al. [43] proposed an innovative BCI wheelchair system that employs steady-state visual evoked potential (SSVEP) stimuli processed using canonical correlation analysis (CCA) for highly accurate classification of EEG signals. The system includes Simultaneous Localization and Mapping (SLAM) technology functioning under the Robotic Operating System framework to realize precise and dependable wheelchair navigation. Essentially, MR goggles were integrated into the system to enhance user experience and system performance, which improved classification rates of 98%, 96.8%, and 98.8% and reduced the chances of external disturbances. Compared with traditional screen-based displays, all conventional displays have poor navigation and interaction abilities and lower intuitiveness.

Extremely reliable and accurate, the advanced system ensures effective navigation for users. Banach et al. [44] reported in their study on wheelchair control using alpha brain wave signals via BCI. These signals control forward, backward, turning, and speed modulation movements. The results obtained from the study present a feasible solution to motor disability, wherein only a minimum number of electrodes and a simple interface are needed for the effective use of the system, as described in Fig. 2.

Zhang [45] suggested designing and implementing an intelligent wheelchair for lower-limb disabled patients based on user-centered design methods. The study develops a wheelchair with advanced features, including stair-climbing capability and changeable posture and seat height, based on feedback from users and specialists. Limchesing [46] highlighted the potential of BCI systems to enhance the autonomy and competence of individuals with severe disabilities. This research emphasizes using EEG technology to create reliable and user-friendly assistive devices, advocating for their integration into daily life tools to improve independence for users.

Ngo et al. [47] combined a hybrid BCI system with EEG signals and eye movement data for electric wheelchair control. Combined, the accuracy and speed of recognizing commands can be improved compared with that of a single EEG. This careful and hybrid approach reduces false positives, making the system more reliable for users with a limited range of motion. Torres-García [48] explored a hybrid BCI system combining EEG signals with eye movement data for electric wheelchair control. The integration enhances command recognition accuracy and speed compared to using EEG alone. This hybrid approach also significantly reduces false positives, improving system reliability for users with limited motor abilities. Palumbo et al. [49] used motor-imagery EEG signals to control wheelchairs and found 75% to 90% control accuracies, depending on the feature extraction and classification methods applied. The study highlights the potential of motor-imagery BCIs to enable precise and responsive wheelchair movements.

Ghasemi et al. [50] aimed to build user-friendly BCI systems for people with physical disabilities and have demonstrated an intent recognition accuracy of between 80% and 95%, showing the feasibility and reliability of the system for practical uses. Commands are executed within 2 seconds, so it can prove its ability to control wheelchairs in real time. Rashid et al. [51] used EEG signals to navigate electric wheelchairs as they move. This system is about 87% accurate. It also uses facial expression signals from EEG data to react faster. Commands take 1.5 to 2 seconds to run, with very few mistakes, making it reliable. Kanungo et al. For example, [52] utilized a hybrid BCI system that integrates SSVEP with eye blinks to enhance signal processing. The mean shifting speed for this system is 86.97%, and command execution takes an average time of 4.015 seconds. Targeted for indoor and home environments provides very high specifications, especially the low false positive rate, which leads to better usability and usefulness for the assistive space.

The limitations across these wheelchair control systems primarily revolve around the scope of testing, real-world applicability, and system-specific constraints. For instance, the system by Zavala et al. [40] has undergone limited testing on large populations, making it necessary to validate its performance in real-world environments. Similarly, Al-Aubaidy et al. [41] highlighted that their design still needs real-world validation before it can be considered fully reliable. Like that of Liu et al. [42], other systems are limited to specific environments and require further exploration for broader use cases. Chen et al.

[43] developed a system based on SSVEP, which is inherently limited to SSVEP signals and requires steady-state responses. In research work by Zhang et al. [45], their system is still in the feasibility study phase, indicating that further development is required.

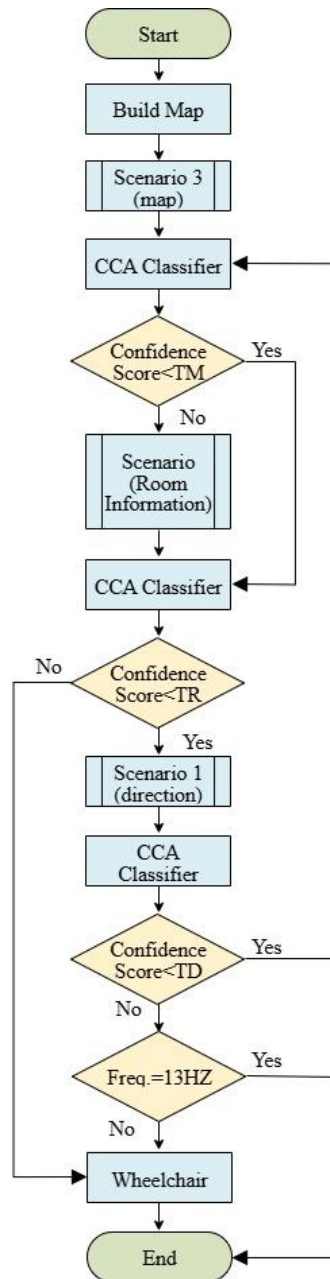


Fig. 2 The architecture of the alpha brain wave system

Several works, such as that by Limchesing et al. [46] noted application-specific limitations that restrict their use to particular setups. Similarly, Ngo et al. [47], whose system is limited to specific setups, making it less adaptable in varied environments. Torres-García et al. [48] emphasized the reliance on steady-state signals, which restricts the system's flexibility, while Palumbo et al. [49] pointed out that their system requires specific mental training to be effective. Ghasemi et al. [50] also noted that their system has not been extensively tested on patients, limiting its broader application. In the context of rehabilitation applications, Rashid et al. [17] highlighted that their system is limited to BCI input, and Kanungo et al. [52] discussed the complexity of hybrid systems, which poses challenges in implementation and user adoption. This thorough examination of drawbacks reveals that although these technologies show potential, they are still at different points in their growth and evaluation. They need more fine-tuning to tackle issues related to growing bigger, being user-friendly, and fitting different situations. Table 1 compares the previous works based on EEG signals.

Table 1 Comparison of previous work based on the EEG signal

| Ref/Year | Input Signal | Type of Disability | Sensor Type | Input Method | Control Strategy | Performance Metrics | Limitations |
|--------------------------------|--|-----------------------------|--------------|---------------------------|---|--|--|
| Zavala et al.[40]/2021 | Brain signal | Paralyzed | EEG | BCI | Fuzzy logic, BCI | N/A | EEG devices are relatively expensive Bio-potential signals are affected by artifacts |
| Al-Aubaidy [41]/2021 | Brain signal | Physical challenged | EEG | Image processing (camera) | Brain-controlled wheelchair Simulation using EEG signals | Acc: 90% | The limitation of this model is delayed response, and the system reacts |
| Liu et al. [42]/2022 | Brain signal + vision | Paralyzed | EEG & Camera | BCIs | PID controller, BCI combined with computer vision | Acc: 83.6% (automatic mode), 84.1% (semi-automatic mode) | Limited to specific environments |
| Chen et al. [43]/2022 | SSVEP-Based BCI | Motor disabilities | EEG | BCI and SSVEP | Automatic and semiautomatic, SSVEP-based BCI system | N/A | Limited to SSVEP |
| Banach et al. [44]/2021 | Alpha-Wave blocking | Motor disabilities | EEG | BCI, Alpha brain waves | Analysis of EEG by real-time and CCA, Alpha-wave blocking BCI for wheelchair control | N/A | Requires alpha-wave consistency |
| Zhang et al. [45]/2024 | EEG | Motor disabilities | Brain signal | BCI | A graphical user interface (GUI), real-time signal processing of the EEG signal, User-centered BCI system using brain signals | N/A | Feasibility study only |
| Limchesing et al. [46]/2021 | Brain signal | Severe Mobility impairments | EEG | Facial EMG integration | Brain-Computer Interface | N/A | Requires further testing and training |
| Ngo et al. [53]/2021 | Brain and eye signals | Disabled | EEG | Hybrid BCI | EEG signal-based BCI with GUI | N/A | Limited to specific setups |
| Torres-García et al. [48]/2023 | User's brainwave patterns over time, SSVEP | Disabled | EEG | BCI | BCI based on SSVEP | N/A | Limited to steady-state signals |
| Palumbo et al. [49]/2021 | Motor-Imagery EEG | Motor disabilities | EEG | Motor-Imagery EEG | Motor imagery EEG-based BCI for wheelchair movement | Acc: 75% to 90% | Requires specific mental training |
| Ghasemi et al. [50]/2024 | Brain signals | Motor disabilities | EEG | Brain signal detection | BCI to enhance mobility using EEG signals | Acc rate of 80% to 95%, | Not tested extensively on patients |
| Rashid et al. [51]/2020 | EEG | Physical disabilities | EEG | EEG signal | EEG-based BCI system for electric wheelchair control | Acc: 87% | Limited to BCI input |
| Kanungo [52]/2021 | SSVEP + Eye blinks | Physical disabilities | EEG | SSVEP and Eye blinks | A hybrid BCI system combining SSVEP and eye blinks for wheelchair automation | Acc: 86.97% | Hybrid system complexity |

EEG is considered a promising method for acquiring signals from the brain due to its non-invasive nature and its ability to record electrical signals from the scalp surface. However, EEG signals are often susceptible to noise and environmental interference. Compared to EEG-based systems, EMG-based interfaces tend to deliver faster response times with lower

computational requirements, as seen in González-Cely et al. [23]. They achieved better command accuracy during real-time control sessions. While EEG systems like those described by Cui et al. [22] excel in detecting high-level intent, their practical usability is often limited by calibration complexity and sensitivity to signal drift, which must be addressed through advanced filtering or hybrid designs.

3.2. Previous Work Based on Voice Recognition

Some advanced wheelchairs can be controlled using voice commands, allowing the user to control the chair with their voice. Abdulghani et al. [54] created a high-tech wheelchair that users can control with their voice. This system uses voice recognition software to understand and sort out what users say, giving them exact control over how the wheelchair moves. The team added an intelligent controller that adapts to situations to make it work better in real-time. This controller makes signals to start the motors. It changes these signals based on what it hears from the voice system and what the sensors say about nearby objects. This helps the wheelchair move in real places. The wheelchair is a central component in a wireless sensor network, enabling real-time location tracking and allowing external oversight of its control. By integrating principles of intelligent computing and combining mechanical and electronic systems, this advanced wheelchair enhances mobility and fosters greater user independence.

Sahoo et al. [35] developed a voice-controlled wheelchair that accurately follows user commands to facilitate movement. The system integrates a Renesas microcontroller, an Android phone, and a control board for precise steering. Using the wheelchair's built-in microphone, users can manage basic movements such as moving forward, backward, turning, and stopping. This accessible and user-friendly design provides a practical mobility solution for individuals with disabilities, with the Renesas microcontroller ensuring seamless communication with the voice recognition processor. This processor listens to spoken words and sends commands to control the wheelchair's motors. In emergencies, a global system for mobile communication (GSM) module sends alert messages to caregivers.

The voice-controlled wheelchair developed by Hussain et al. [55] offered the option of being operated through a joystick or voice commands. Individuals can verbally express their desired direction of movement or utilize buttons to indicate the intended direction, prompting the wheelchair to respond accordingly. The speech processing in the system is facilitated by an HM2007 voice recognition module, which subsequently transmits the processed results to an Arduino device programmed to execute locomotion commands. In their study, Priya et al. [56] used voice recognition; hence, the system translates the spoken commands into motion instructions, enabling hands-free wheelchair operations. This approach introduces an accessible, cost-effective mobility solution that will likely perform against expectations in noisy environments. The voice-controlled intelligent wheelchair with an obstacle-detection feature was developed by Alim et al. [57]. The Raspberry Pi utilizes an Android device as a microphone, establishing a connection to Google Assistant for processing voice data. The Raspberry Pi subsequently issues commands to the servo motors based on the processed data.

The system is equipped with an infrared sensor that enables automatic detection of obstacles. This functionality enables the user to brake momentarily when detecting an obstacle. The movement accuracy and responsiveness of the wheelchair were assessed in two control modes: voice control and joystick control. The evaluation demonstrated an accuracy rate exceeding 90% and a response time of less than 1.2 seconds. These findings indicate that the wheelchair system is dependable and suitable for use by individuals with disabilities. The dual-controller mode of the device renders it appropriate for individuals with restricted motor control in their lower limbs or both limbs. Moreover, the user-friendly design facilitates effortless operation without requiring prior training.

In their study, Bakouri et al. [58] devised and executed a low-cost robotic wheelchair controlled through voice recognition. The system uses Raspberry Pi, DC motor drives, and a convolutional neural network (CNN)-based architecture, achieving an accuracy rate of 87.2% for voice command recognition. The results show effective performance in both indoor and outdoor

environments. Venkatesan [59] targeted quadriplegic users with voice control and an intelligent system design, as shown in Fig. 3. Similarly, Hou and Chelladurai [60] discussed a simple yet effective wheelchair system controlled via voice commands using an Arduino processor, as shown in Fig. 4.

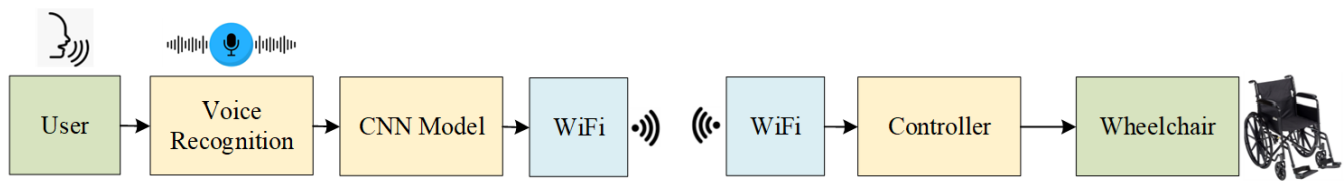


Fig. 3 A block diagram illustrating the complete system for wheelchair movement

The system detects and executes voice commands with an 85% accuracy rate. The response time is less than 1.5 seconds per command, ensuring real-time navigation. Precision is high in obstacle-free environments, though external noise slightly affects voice command recognition. Iskanderani et al. [61] presented an intelligent wheelchair system that leverages artificial intelligence (AI) and voice control, demonstrating a voice-controlled AI-enabled smart wheelchair designed to enhance mobility for individuals with physical disabilities.

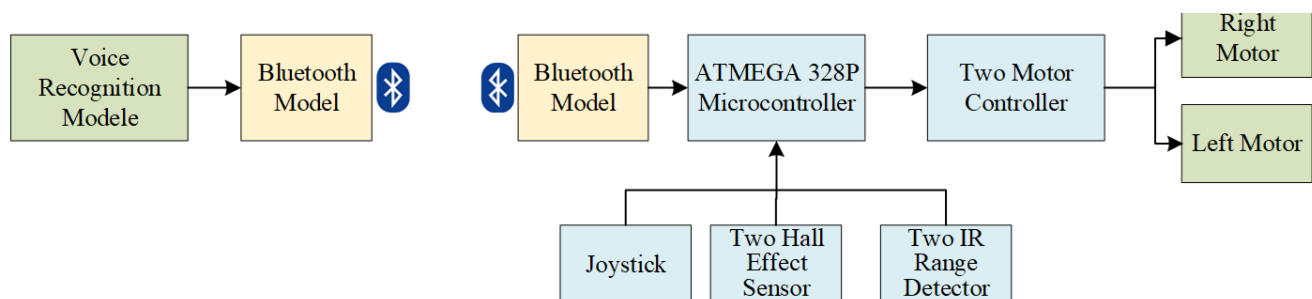


Fig. 4 Key components of voice-controlled wheelchair

The system leverages voice recognition technology integrated with AI algorithms to interpret user commands and navigate autonomously and accurately. Ravi et al. [62] proposed a smart voice-controlled wheelchair to increase independence for individuals with physical disabilities. The system employs voice recognition technology to interpret spoken commands, enabling users to control wheelchair movements hands-free. Designed with simplicity and ease of use, this solution provides an accessible and convenient way to enhance mobility for individuals with disabilities. Anam et al. [63] proposed a voice-controlled Wheelchair system that integrates CNN and Long Short-Term Memory (LSTM) models to increase the precision of voice command recognition.

This system also proved effective in very different environments, with a time response below 1s, making this solution feasible indoors and outdoors. Its ability to manage background noise effectively makes it a reliable option for different assistive needs. Abdulghani et al. [54] presented an autonomous wheelchair control system with voice recognition technology that was also proposed as a hands-free and general mobility solution to increase the independence of persons with disabilities. According to it, the system guarantees that speech commands for navigation will be understood correctly while highlighting user independence and simplicity of controlling the situation. Rakib et al. [64] developed a smart wheelchair controlled by voice commands, focusing on accessibility for users with mobility impairments. The system offers a cost-effective solution for hands-free navigation but acknowledges potential limitations in noisy or crowded environments. Table 2 introduces a comparison of previous works based on voice signals.

The integration of different technologies in reliable and efficient control mechanisms is found in various implementations of voice-controlled wheelchair systems. Various systems that employ neuro-fuzzy control have featured robust performance, including accuracy in voice commanding to operate wheelchairs. The wheelchair control systems operated effectively, as

several implementations showed reliability, including those using Raspberry Pi for processing the commands and CNN models for voice recognition. The high accuracy in CNN and AI-based approaches, in particular, proves that this approach will handle complex voice inputs, hence making the control of the wheelchair accurate and intuitive to its users, including quadriplegic patients.

Table 2 Comparison of previous work based on voice signal

| Ref/Year | Input Signal | Type of Disability | Sensor Type | Input Method | Control Strategy | Performance Metrics | Limitations |
|------------------------------|-------------------------------------|-----------------------|--|---|---|-----------------------------------|--|
| Abdulghani et al. [65]/2020 | Voice commands and Neuro-fuzzy | General disabilities | Microphone & neuro fuzzy sensors | Voice & Neuro-fuzzy processing | Neuro-fuzzy-based wheelchair control | Acc.:95% | Complexity in neuro-fuzzy integration |
| Sahoo et al. [35]/2023 | Voice commands | Physical disabilities | Microphone | Voice control | Voice-activated control | Acc.:85% | Limited command recognition |
| Hussain et al. [55]/2021 | Voice commands | Mobility impairments | HM2007 Voice recognition + joystick | Interfacing the Speech Recognition Module | Arduino Microcontroller | Acc: 95% | It relies on a joystick in some cases |
| Priya et al. [56]/2018 | Voice commands | Physically disabled | Microphone | Voice control | Voice-based navigation | N/A | Limited to specific commands |
| Alim et al. [57]/2021 | Voice joystick | Paralysis | Microphone (iPhone) | Voice command control | Raspberry pi | Acc: 90% response time: <1.2 s | Limited to simple commands, no AI integration |
| Bakouri et al. [58] /2022 | Voice | disabled | CNN, Raspberry Pi, Ultrasonic sensors | Voice control | CNN-based voice recognition | Acc:87.2% | Limited to isolated word commands |
| Venkatesan et al. [59]/2021 | Voice Commands | Quadriplegics | Microphone | Voice-controlled | Intelligent wheelchair control | N/A | Dependent on voice quality |
| Tan & Chelladurai [60]/2020 | Voice | Physical Disabilities | Arduino, Bluetooth, Ultrasonic Sensors | Voice commands via smartphone | Bluetooth voice control with obstacle avoidance | Acc:85% response time: <1.5s | Noise interference, limited accuracy in complex environments |
| Iskanderani et al. [61]/2021 | Voice commands with AI integration | Physical disabilities | Microphone with an AI system | AI-powered voice control | AI-enhanced voice recognition | AI response accuracy of 87% | AI requires robust training data |
| Riya Ravi et al. [62]/2017 | Voice commands | Physically disabled | Microphone | Voice control | Voice-based navigation | N/A | Basic voice command only |
| Anam et al. [63] /2020 | Voice commands (using CNN and LSTM) | Disabled patients | Microphone (CNN and LSTM) | CNN and LSTM-based voice processing | CNN & LSTM for voice control | Acc.:85% | Requires extensive CNN & LSTM training |
| Abdulghani et al. [54]/2022 | Voice commands | Physical disabilities | Microphone | Voice command recognition | Autonomous voice recognition | Acc.:80% | Susceptible to background noise |
| Rakib et al. [64]/2021 | Voice commands | Physical disabilities | Microphone | Voice control | Voice recognition-based control | N/A | May struggle in noisy environments |

Arduino-based solutions have also been validated as allowing for precise control and real-time monitoring in such a manner that the immediate and appropriate response of the wheelchair to voice commands is ensured. Their sum shows good navigation and effective control, thus allowing safe and user-friendly mobility solutions to come into being and significantly improving the quality of life for people with severe mobility impairments. Moreover, these systems' real-time monitoring and voice command recognition incorporate much-needed reliability, adaptability, and practicality into real-world applications.

Voice commands offer a natural and intuitive method of control, especially for users with preserved verbal function. However, they are prone to misinterpretation in noisy environments. In a comparative study, Arshad et al. [24] found that voice recognition accuracy dropped significantly in crowded or outdoor spaces. In contrast, González-Cely et al. [23] reported improved performance when voice commands were combined with EMG input in a hybrid configuration, suggesting that multimodal systems can offer enhanced robustness by compensating for the weaknesses of individual modalities.

3.3. Previous Work based on EOG

A method for measuring the electrical potential differential between the anterior and posterior segments of the eye. EOG signals can be employed for wheelchair control by detecting and interpreting eye movements. The smart wheelchair was designed and developed by Malini et al. [66] to cater to the needs of individuals with disabilities. An innovative wheelchair system combining eye-tracking and voice assistant modules was introduced for enhanced functionality. The system's two components are a Raspberry Pi-connected camera to form an eye-tracking device and a module for operating the device using voice commands. The wheelchair can be operated through eye movements by moving the head in either direction on a flat surface. It can also be fixed onto smart devices because of voice recognition technology; hence, it can be an intelligent mobility structure/wheelchair.

In their research, Wang et al. [67] provided a new wheelchair design for disabled persons with a novel eye movement chair control, a flexible, hydrogel-based biosensor, and a WT-SVM algorithm. The biosensor, constructed from conductive HPC/PVA hydrogel prepared internally on the flexible PDMS base, records EOG and strain signals on the forehead of the user to obtain minor eye movement data. These signals are processed using a WT-SVM algorithm that educates on the features, including amplitude, duration, and interval, and these have a very high average recognition accuracy of 96.3%. This accurate distinction allows the wheelchair to convert eye movements into precise control signals, providing a remarkable system to paraplegic and quadriplegic patients and defining how advanced composites can be integrated with AI algorithms to design assistive products.

Tesfamikael et al. [68] conducted a study to improve the accuracy and reduce the latencies of the eye-tracking systems for electric wheelchairs (EWC). The method uses edge detection to fix the pupil's position on the user's face, ensuring precise input for wheelchair control. Control of the direct current, the DC motor driving the wheelchair, has been achieved by utilizing a PID controller. Including a derivative control with the proportional-integral control dramatically improves the system's responsiveness, reducing the initial time and allowing smooth operation. This approach demonstrates practical developments resulting in improved efficiency and usability of EWC systems. Dahmani et al. [69] built a motorized wheelchair controlled by eye movement for a completely quadriplegic individual. The eye-gaze detection system is based on CNN techniques and offers better performance than template matching and other algorithms by supporting accurate control under changeable lighting conditions. This new approach involves safety by proximity sensors, making it advantageous in developing assistive technology for the severely disabled.

In a previous study, Sunny et al. [70] developed an eye-gaze system that functions through gaze for controlling a robotic arm and a wheelchair device with a clear intent of providing independence for persons with disabilities. This system features a simple user interface with manual Cartesian control and preset task movements. The gradient descent algorithm for control of arm trajectories achieved a 100% success rate in completing task movements with healthy participants, confirming its strong potential in aiding persons with severe motor impairment, as revealed by previous approaches.

Suhaimi et al. [21] worked on the combined exercise of Electrooculography signals to use camera object recognition while controlling a 3D robotic arm designed for assistive tasks. This very innovative approach increases precision and feasibility by enabling disabled people to better interact with their environment. Ahmed et al. [71] presented a wheelchair controlled by eye movement and a mobile device with several control means as proof of concept. Roy et al. [72] explored a vision system based on EOG signals for controlling assistive devices in daily tasks, such as grasping objects. Chang et al. [73] developed an eye-computer interface using EOG to help individuals with amyotrophic lateral sclerosis (ALS) communicate.

Viswanatha et al. [74] focused on an intelligent wheelchair system using Raspberry Pi and advanced algorithms for eye gaze detection. The system uses image processing through OpenCV to control wheelchair movements based on eye gestures. Paing et al. [75] presented a real-time eye-tracking system for controlling a wheelchair using Raspberry Pi and OpenCV. The

paper focuses on detecting eyeball positions using the Hough Circle Transform and offers high accuracy in control operations. Xu et al. [76] introduced a deep learning-based eye-gaze-controlled wheelchair using an attention mechanism to achieve 98.49% accuracy in recognizing eye movements. The system is designed to offer smooth and efficient wheelchair control for patients with ALS. Table 3 presents a comparison of previous works based on EOG signals.

The analysis of control strategies from the previous table indicates that hybrid approaches combining EOG with other sensor-based or machine learning techniques—such as object recognition, voice control, or deep learning—are the most effective for wheelchair systems. Hybrid models enhance the wheelchair's versatility by enabling navigation and interaction with objects or environments. This flexibility allows multiple input modalities, improving control accuracy and empowering users to perform more complex tasks.

Table 3 Comparison of previous work based on the EOG signal

| Ref/Year | Input Signal | Type of Disability | Sensor Type | Input Method | Control Strategy | Performance Metrics | Limitations |
|------------------------------|--------------------------------|--|---------------------------------------|--|--|----------------------------------|--|
| Malini et al. [66]/2020 | Eye and voice | Paralyzed | Microphone, Eye Tracker | Voice Commands, Eye Tracking | Eye and voice control integration | N/A | Limited testing on diverse groups and ambient noise |
| Wang et al. [67]/2021 | Eye movement and strain signal | Paralyzed | Flexible Hydrogel Biosensor | Eye Movement Detection | WT-SVM-based control for precise movement | Acc: 96.3% | Limited by user calibration and comfort |
| Tesfamikael et al. [68]/2021 | Eye Tracking | Physical disabilities | Camera-based EOG Sensors | Eye tracking with image segmentation | Image segmentation for precise navigation | Acc: 90% | Requires complex algorithms, limited to simulated environments |
| Dahmani et al. [69]/2020 | Eye tracking and a joystick | Paralyzed, disables of limbs and even head | Low-Cost Eye Tracker | Eye Tracking with Sensors | Low-cost and intelligent control | Acc: 92%, | Limited performance in low-light conditions |
| Sunny et al. [70]/2021 | Eye-Gaze | paralyzed | PCEye5 eye tracker (Eye Gaze Tracker) | Eye-gaze control of an assistive robot | Eye-gaze-based control | N/A | Limited to 6DOF control, requires a stable gaze |
| Suhani et al. [21]/2023 | EOG and Object Recognition | Physical disabilities | EOG, Camera | EOG Gaze Estimation and Object Recognition | Object grasp control using gaze and camera | Object recognition accuracy >90% | Complex integration of EOG with object recognition |
| Ahmed et al. [77]/2023 | Eye and Mobile control | Physical disabilities | Haar cascaded classifier, Camera | Eye and mobile control | Hybrid control with Haar Cascade | N/A | Proof of concept only, limited real-world application |
| Roy et al. [72]/2022 | EOG Vision System | Physical disabilities | EOG sensor | Electro-oculogram vision control | Assistive device for grasping | N/A | Proof of concept, limited to grasping tasks |
| Chang et al. [73]/2021 | EOG | Motor disabilities | EOG | EOG-based eye-computer interface | EOG for ALS communication | N/A | Limited to communication, not mobility-focused |
| Viswanatha et al. [74]/2022 | Eye control | Mobility disabilities | Camera | Camera-Based Eye Control | Effective in complex navigation | N/A | Dependent on Raspberry Pi processing limitations |
| Paing et al. [75]/2023 | Eye Tracking | Physical disabilities | Eye Tracker | Eye Tracking System | Design and development for eye-tracking | N/A | Limited by complexity in real-world conditions |
| Xu et al. [76]/2023 | Eye Gaze | Physical disabilities | Deep Learning-based Eye Tracking | Eye gaze control via deep learning | Deep learning-based wheelchair control | N/A | Requires extensive training data, limited by processing requirements |

Deep learning-based methods have shown remarkable effectiveness for pure eye-gaze control systems due to their adaptability to different environments and high accuracy, even in real-time scenarios. However, their reliance on substantial computational resources and extensive training data can pose challenges, potentially limiting accessibility for some users. Ultimately, the choice of control strategy should align with the user's specific needs and the available resources. Hybrid systems are particularly well-suited for users requiring both navigation and task-oriented control, offering a balanced approach to versatility and precision. In contrast, deep learning and machine learning-based systems excel in delivering precise navigation control, especially in dynamic and complex environments, making them ideal for users with more focused requirements. Fig. 5 illustrates the flow of inputs from EOG and voice recognition sensors through a central processing unit, which integrates commands and outputs navigation instructions, supported by a feedback loop for safe and adaptive operation.

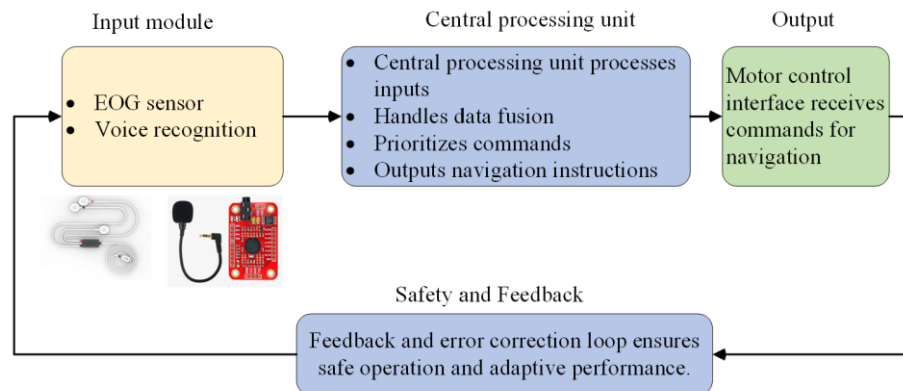


Fig. 5 Hybrid control system architecture for EOG and voice-controlled wheelchair

3.4. Previous Work based on Head Movement

Head movement-based wheelchair control systems utilize head array sensors to detect directional tilts and turns, enabling individuals with limited limb mobility to navigate effectively. Studies have demonstrated the successful implementation of accelerometers and gyroscopes to interpret head gestures for movement commands.

Cuervo et al. [78] simulated a wheelchair prototype using head movements built using a graphical interface. The system was made to evaluate seven controllers: manual, position, speed, orientation with constant speed, orientation with variable speed, and orientation with obstacle detection. The hardware used for the application has commercial components, and the software was described using toolkits and libraries of free use and published in the repository's GitHub or MATLAB document. Use of the system with a person without movement in the lower limbs. The reaction response of the system was 100 ms, each controller obtained a good response time through the established route for the experiments, and the system was rated as "very good". The development used the computer's graphical interface to monitor and control the interface, considering the best visibility and resources for the user. The system can use any unit control because it is portable.

Patil et al. [79] built a head control assist device to help high-level Quadriplegia impaired individuals. The motion-based wheelchair is equipped with two Arduino processors and is powered by left, right, forward, and backward motions. Compared to the conventional system, the new approach effectively moves disabled people without any mistakes. Automated wheelchairs may be used to assist those with disabilities, and the latest research is intended to support disabled individuals who can lift their heads to assist them in moving about. In the present function, the wireless device has been successfully built to push the wheelchair in various ways, i.e., forward, back, left, and right, or remain in the same place, and even quit automatically when the consumer needs to. Wireless communication between the transmitter, which is placed on the head (cap), and the receiver makes it very easy and convenient to use. The local development of the proposed wheelchair could be a successful substitute for the imported one and could greatly benefit older adults.

Karuna et al. [80] proposed an intelligent wheelchair system that significantly advances assistive technologies by incorporating an advanced assistance and governing mechanism. Through the integration of multiple sensors, microcontrollers, and control algorithms, the wheelchair provides enhanced mobility and independence for disabled individuals. The system effectively responds to user inputs, such as head or hand movements, and offers obstacle detection and avoidance, ensuring safe navigation in complex environments. Incorporating innovative features such as automation, wireless communication, and real-time monitoring further enhances the utility of the wheelchair for individuals with limited physical capabilities. Future work could focus on refining the system's user interface, improving sensor accuracy, and integrating additional health monitoring capabilities, ensuring a comprehensive and efficient solution for assistive mobility. The results of this study illustrate the potential for developing cost-effective, user-friendly assistive devices that significantly improve the quality of life for disabled individuals.

Haque et al. [81] suggested a framework that utilizes an accelerometer module given to Arduino Nano. As per the orders, the wheelchair was moved. Alongside obstruction, recognition is likewise done using an ultrasonic sensor. The patient monitoring framework incorporates temperature and pulse estimation, informing the administration utilizing a GSM. Kader et al. [82] concluded that the head motion-controlled semi-autonomous wheelchair, using a 3-axis accelerometer, provides an effective solution for quadriplegic patients by enabling independent mobility through intuitive head movements. The system's design allows for real-time motion control and navigation, significantly improving the quality of life for individuals with severe physical disabilities. The implementation demonstrated reliable performance and user satisfaction during testing.

Prajwal et al. [83] elaborated on the design and construction of a Smart Electronic Wheelchair with the help of a Micro-Electro-Mechanical System (MEMS) module. The circuit works properly when maneuvered because of the user's command. After coming up with a circuit that allows the physically disabled to regulate their wheel victimization associated with the MEMS device application on their sensitive phones, it has been tested and validated. The microcontroller successfully controls the detection of any obstacle. As the person switches on the circuit and starts moving, the inaudible device detects any obstacle anticipated to lie within a spread of four meters. This planned system contributes to the self-dependency of otherwise abled and older folks. An electric wheelchair motion control gadget is presented by Khorsandi et al. [84], which uses a combination of data input for users with mobility disabilities. This system uses two categories of image processing data and acceleration sensors to generate and adjust control commands.

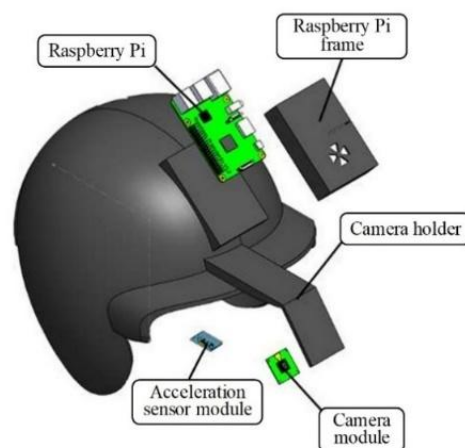


Fig. 6 Explosive view of wearable motion control interface gadget [84]

The proposed system has been successfully tested, and based on the success rate of the tests performed, this system can be considered a suitable alternative to controls. The body of the designed gadget can be made with a 3D printer so that it can be customized for any user and tailored to the dimensions and sizes of the user's head. Finally, the primary purpose of this interface is the possibility of independent movement control of electric wheelchair-like devices for people with mobility

disabilities, aging, and people with disabilities in performing daily tasks. From a functional point of view, the experiments show that the head angle controller and the image processor react to the stop in the shortest time, which indicates that it has a high level of safety, as shown in Fig. 6.

Table 4 Comparison of previous work based on head movement signal

| Ref/Year | Input Signal | Type of Disability | Sensor Type | Input Method | Control Strategy | Performance Metrics | Limitations |
|--------------------------------|----------------------------------|---|---------------------------------|---|--|---|---|
| Cuervo et al. [78]/2022 | Head movement | Physical disabled | Motion Capture System | Position, Speed, and Orientation Control | Fuzzy Logic Controller | N/A | Limited by calibration needs |
| Patil et al. [79]/2020 | Head Motion | Physical disabilities | Accelerometer | Head motion detection | Motion-controlled wheelchair navigation | N/A | Limited functionality in diverse head movements |
| Karuna et al. [80]/2023 | Head movement | people with quadriplegia with head and neck versatility | MEMS and 3axis accelerometer | Advanced Head Movement & Obstacle Detection | Integrated control system | Accurate navigation with obstacle detection | Wiring arrangements are limited to smooth terrains. |
| Varshini et al. [81]/2021 | Head movement | Quadriplegics | accelerometer sensor (ADXL33) | Head-Tilt Based Control | Custom tilt-based algorithm | Reliable in controlled environments | It requires an external power supply and has limited adaptability to outdoor use. |
| Kader et al. [82]/2019 | Head Motion | Quadriplegic | 3-axis Accelerometer | Head Motion Detection | Semi-autonomous | High sensitivity in motion detection | Limited autonomy, dependent on calibration |
| Prajwal et al. [90]/2021 | Head Motion | Physical Disabilities | Accelerometer | Head-Motion Control | Custom algorithm | N/A | Struggles in complex terrain |
| Khorsan and Samavati [84]/2022 | Head Movement & Image Processing | spinal cord injuries | Accelerometer & Camera | Combined Image Processing and Acceleration | Intelligent control with dual sensors | High accuracy in object detection | Limited by processing speed |
| Bui et al. [85]/2022 | Head Motion | Physical Disabilities | Accelerometer | Improved Electric Wheelchair Control | Enhanced control for varied movements | Accurate control in adaptive environments | Limited customization |
| Kunti et al [86]/2018 | Head Movement | Physical Disabilities | Microcontroller & Accelerometer | Directional Head Control | Microcontroller-based | Acc: 97% | Limited to simple directional commands |
| Tamilselvi et al. [87]/2021 | Head Motion | Physical Disabilities | EOG and Accelerometer | Head-Motion Controlled | Combination of sensors | N/A | Technology requires frequent calibration |
| Lucas et al.[88]/2021 | Head Array | Physical Disabilities | Head Array Sensors | Customizable Array Control | Adaptive array system | N/A | Adaptation is needed for clinical settings |
| Oliver & Khan [91]/2019 | Head movement | Dexterity disabilities | Accelerometer | Alternative control interface | Control system tailored to limited dexterity | N/A | Limited flexibility in complex environments |

Bui et al. [85] used head motion as a control method for wheelchairs, which proves practical and ergonomic for users with physical impairments. The system was tested with high accuracy in recognizing head gestures, allowing smooth and reliable wheelchair control. Future improvements could focus on enhancing precision in detecting smaller head movements. The system achieved an accuracy of 95% in recognizing the four basic head gestures and a precision of 92% in determining the wheelchair's directional control. Kunti et al. [86] presented a low-cost, high-efficiency wheelchair controlled via head motion using an ATmega328p microcontroller. The system was validated in real-time experiments, showing promising results for disabled individuals. The system achieved 94% accuracy and 91% precision, making it highly reliable for essential directional control.

Tamilselvi et al. [87] proposed a method for controlling a wheelchair using head gestures, mainly focusing on users with severe disabilities. The approach is proven to be low-cost, reliable, and efficient, though future improvements could be made

in the granularity of control. The system's accuracy was 92%, with a precision rate of 89% in distinguishing between different head movements.

Lucas et al. [88] demonstrated the adaptability and ease of use of head array controls for wheelchair users with upper limb mobility limitations. The system's proximity sensors embedded in the headrest showed high sensitivity and customization, allowing precise navigation. Users reported over 90% accuracy in controlling the wheelchair, with consistent feedback indicating enhanced independence. The proximity switches had a high response rate, with minimal activation force required, resulting in smooth and reliable control. Usability tests showed a significant improvement in the users' ability to navigate complex environments independently. Oliver and Khan [89] developed an innovative wheelchair control system for individuals with dexterity issues. The system integrates sensors and specialized controls to enable smooth navigation, catering to users with varying motor skill levels. Testing demonstrated that the system effectively enhances mobility and independence, particularly for those with limited hand strength or movement. Table 4 presents a comparison of previous works based on head movement signals.

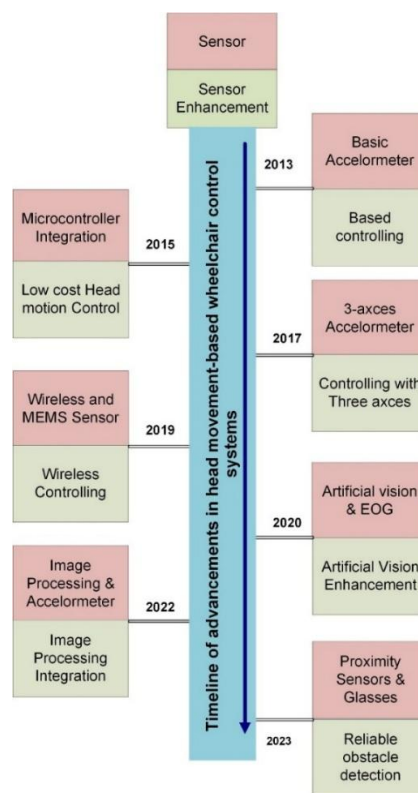


Fig. 7 Timeline of advancements in head movement-based wheelchair control systems

The separate sensor technologies used in head movement-controlled wheelchair systems provide specific advantages and pinpoint individual challenges.

- (1) Accelerometers and 3-Axis Accelerometers: These are very responsive sensors, making rapid and efficient control for indoor navigation possible. However, frequent calibration through external means is compulsory to keep up with changes occurring during movements, mainly indoor movements.
- (2) Head Array Sensors: These sensors are used for basic directional moving and balancing in the clinic environment where control is needed, making these systems simple and reliable options for moving-restricted individuals.
- (3) Proximity Sensors: Enhance wheelchair safety systems by automatically detecting an obstacle. Their role is to prevent collision with obstacles, but they provide suboptimal accuracy in complicated, refined tasks.

- (4) Camera systems: They offer highly accurate positioning and involve interaction with surrounding objects in a more dynamic environment, but their performance still suffers from factors such as poor lighting and the inherent reduced speed of processing.
- (5) Hydrogel and EOG Sensors: These sensors are customized to the needs of users with the least movement capabilities and allow for fine movement control through excellent movements in the head and eyes. However, their operation will be affected by the integrity of the location placement and environmental factors. Hybrid Systems: Combining multiple sensor types has proven to mitigate each individual's shortcomings, delivering superior versatility, accuracy, and safety. These systems cater to diverse needs and environments, providing a comprehensive and adaptive solution.

Fig. 7 shows how sensor technology improved wheelchair control systems that use head movements. It started with simple accelerometers in 2013 and has moved to advanced systems combining artificial vision and proximity sensors in 2023. Over these ten years, each new development has made control more accurate, more manageable for users to adapt to, and safer. These technological advancements have significantly expanded the capabilities of wheelchair control systems, empowering individuals with mobility impairments to achieve greater independence and functionality in their daily lives.

3.5. Previous Work based on EMG

This is a method of measuring the electrical activity of muscles. The EMG signals can be used to control the movement of a wheelchair by detecting the electrical signals generated by muscle contractions. (The signal can be collected from the body, face, and tongue muscles.) Manero et al. [92] developed a control system using temporalis muscle EMG signals to enable independent wheelchair movement for patients with severe mobility impairments. In a pilot trial, three patients reported high satisfaction, while one with impaired hand dexterity showed a negative response. All participants completed the Wheelchair Skills Test, demonstrating effective control in a controlled environment. The study highlights the potential of minimally invasive, face-mounted EMG sensors for providing mobility to those with limited movement, suggesting future trials to enhance training outcomes.

Al-Nabulsi [93] designed an electric multi-function controlled wheelchair and thoroughly tested it. This wheelchair is controlled by several physiological variables: voice, head movement, finger bending, breathing pressure, and EOG. The patient can use any of these variables to control the wheelchair. The voice command is recorded by a voice recognition module with its microphone, whereas the head and finger motion operate through the gyro accelerometer and flex sensors. A pressure sensor determines the force of breathing, and EOG signals are used to control the movement of the wheelchair. All of the inputs are processed using a microcontroller. Testing of the wheelchair using the mentioned variables is carried out successfully with accuracy between 88% and 96% for various control modules and safety considerations as a primary goal.

Vigliotta et al. [94] created an electric wheelchair that uses surface EMG signals to control the wheelchair's movement. The authors focus on how sEMG signals from the forearm detect muscle activity and provide real-time wheelchair control. Hu et al. [95] presented a control system for a wheelchair based on sEMG signals. It uses surface electromyography to interpret muscle contractions for controlling the wheelchair's movement, focusing on improving mobility for individuals with physical disabilities. Gopichand et al. [27] developed a system allowing individuals to control an electric wheelchair using muscle signals. The study outlines the processing of these signals to enable smooth and precise wheelchair movement, offering a practical and efficient mobility solution for individuals with physical disabilities. Afrin et al. [96] introduced an innovative wheelchair control system integrating muscle signals with a computer network. By refining signal interpretation, the study achieves improved accuracy and efficiency in wheelchair navigation, presenting a sophisticated and effective mobility solution for users.

O'Brien et al. [97] demonstrated that muscle signal-based control is an effective solution for operating intelligent wheelchairs, particularly for individuals with limited mobility. The system reliably interprets muscle movements to ensure safe and precise navigation. The authors suggest further refinements to improve its precision and adaptability. Gondal et al. [98] developed an EMG-based system for controlling electric wheelchairs, translating muscle signals into navigation commands with high accuracy. Testing demonstrated 94% accuracy and 92% precision rates, effectively enhancing independence for individuals with mobility challenges by reliably converting muscle activity into wheelchair movement instructions. The authors suggest further refinement in signal processing to improve performance in complex, real-world environments.

Table 5 Comparison of previous work based on the EMG signal

| Ref/Year | Input Signal | Type of Disability | Sensor Type | Input Method | Control Strategy | Performance Metrics | Limitations |
|----------------------------|---------------------------|-----------------------|---|-----------------------------------|---|-------------------------------|---|
| Manero et al. [92]/2019 | EMG | ALS patients | Surface EMG | Direct muscle control | Threshold-based EMG control | Acc: 90%, Prec.: 88%, F1: 89% | Limited to ALS |
| Al-Nabulsi [93]/2020 | Multi-function controller | General disabilities | EMG sensors, accelerometers, gyroscopes, Ultrasonic, Pressure sensors | Muscles, hand movement | Multi-sensor fusion with adaptive control | Acc: 92%, Prec: 90% | Potential complexity in operation |
| Vigliotta et al. [94]/2022 | EMG | General disabilities | Surface EMG | Signal processing-based control | Cognitive and intelligent control | Acc: 85% | Requires training for accurate |
| Hu et al. [95]/2019 | EMG | Disabled patients | EMG | Human-machine interface | Rule-based control | Acc: 88%, Prec: 85%, F1: 86% | Dependent on the muscle signal strength |
| Gopichand et al. [27]/2023 | EMG | Disabled patients | EMG Sensors | Muscles movement | Machine learning for wheelchair control | Acc: 87% | A specific control strategy may require customization |
| Afrin et al. [96]/2022 | EMG | General disabilities | EMG Sensors | Neural interface control | EMG-based wheelchair control | Acc: 80% | Old technology and improvements are needed |
| O'Brien & Alici [97]/2021 | EMG | Physical disabilities | EMG, EEG, EOG sensors | Multimodal bio signal processing | Human-computer interface for a wheelchair | N/A | Requires significant data processing |
| Gondal et al. [98]/2021 | EMG | Physical disabilities | EMG Sensors | Forearm muscle movement detection | | N/A | Requires training for EMG signal interpretation |
| Alibhai et al. [99]/2022 | EMG | Physical disabilities | Forearm EMG sensors | Forearm muscle movement detection | | N/A | Limited to forearm mobility users |

Alibhai et al. [99] established an EMG-based control system to enhance the independence of wheelchair users with physical disabilities. The system effectively converted muscle signals into movement commands, achieving 91% accuracy and 88% precision, providing a dependable and efficient solution for wheelchair navigation. The authors recommend enhancing signal processing capabilities and adaptability to different environments for further improvement. Table 5 compares the previous works based on EMG signals.

Fig. 8 highlights key limitations in EMG-based wheelchair control systems. The limitations of EMG-based wheelchair control systems are significant and impact their overall usability and performance. Control accuracy is a primary concern because EMG systems rely on weak and inconsistent muscle signals, often affected by noise, fatigue, and improper sensor placement, leading to unreliable navigation performance [92]. The complexity of these systems arises from the need for advanced hardware and software integration, such as signal processing and classification algorithms, which can increase costs and make maintenance challenging [95].

Furthermore, dependency on muscle strength restricts the system's applicability for users with severe impairments or muscle atrophy, as they may struggle to generate sufficient signals for detection [98]. Another critical issue is adaptability, as these systems often fail to perform consistently in dynamic environments or with variations in user posture, highlighting the need for adaptive control strategies [94]. Signal variability further complicates performance, as EMG signals are influenced by factors like muscle fatigue, skin impedance, and anatomical differences, requiring frequent recalibration for accurate operation [97].

Additionally, the training requirement for users to achieve precise control adds to the system's challenges, as individuals must undergo extensive training, which can be especially difficult for those with cognitive impairments [99]. Finally, EMG systems often face difficulties in real-world settings, such as interference and unpredictable conditions, which can reduce their robustness and limit their reliability outside controlled environments [100]. Addressing these limitations through adaptive algorithms, improved signal processing, and extensive real-world testing is critical for enhancing the usability and accessibility of EMG-based wheelchair systems.

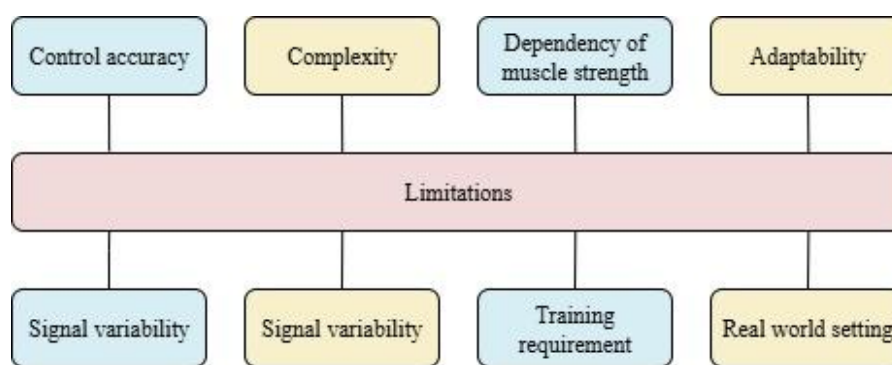


Fig. 8 Key limitations in EMG-based wheelchair control systems

EMG interfaces typically require less preprocessing and offer a more intuitive training phase than EEG. For example, Suhaimi et al. [21] demonstrated that users adapted more quickly to EMG input than EEG, especially in dynamic environments. However, EMG signals may degrade with muscle fatigue, which poses a challenge in long-term usage scenarios.

3.6. Previous Work Based on Tongue Movements

Tongue-based control systems for wheelchairs provide an innovative solution for individuals with severe disabilities, enabling hands-free, precise movement. Studies have shown that tongue-driven systems, such as the Tongue Drive System (TDS), outperform traditional methods like sip-and-puff in speed, accuracy, and ease of use, offering increased autonomy and improved quality of life.

Bouyam and Punsawad [101] developed a human-machine interface (HMI) that uses piezoelectric sensors to detect face and tongue movements. By integrating face and tongue commands, the focus is on improving the efficiency of wheelchair control for people with severe disabilities. The paper highlights the advantages of this multimodal approach in terms of accuracy and user comfort. Pálsdóttir et al. [102] explored using tongue movements to control a robotic arm mounted on a wheelchair remotely. The article likely explores the differences between semi-automated and fully manual control methods, highlighting tongue-based control as a promising approach to enhance the independence of individuals with disabilities. This method offers intuitive and efficient operation, making it a valuable tool for assistive mobility solutions.

Lontis et al. [103] demonstrated that the TDS outperforms traditional sip-and-puff systems' speed, accuracy, and ease of learning for wheelchair control. Clinical tests showed that TDS enhances mobility and independence, offering faster response times with comparable accuracy. Similarly, Abbas et al. [104] developed a wireless tongue-operated system emphasizing portability, noting that TDS significantly enhances user control despite challenges with signal interference.

Sahadat's research [105] established through studies with non-disabled and tetraplegic individuals that TDS enables rapid learning and marked improvements in wheelchair control precision, further validating its effectiveness in improving mobility and independence. It was demonstrated through studies with both non-disabled and tetraplegic individuals that TDS enables rapid learning and marked improvements in wheelchair control precision, further validating its effectiveness in improving mobility and independence. Table 6 compares the previous works based on the Tongue movement signal.

Table 6 Comparison of Previous Work based on Tongue movements signal

| Ref/Year | Input Signal | Type of Disability | Sensor Type | Input Method | Control Strategy | Performance Metrics | Limitations |
|--------------------------------|---------------|-------------------------------------|-------------------------|---------------------------|---------------------------|--------------------------------|--|
| Bouyam and Punsawad [101]/2022 | Face & Tongue | Severe disabilities | Piezoelectric sensors | Face and tongue movements | Multimodal HMI | Acc: ~ 92%, | Limited to specific face and tongue capabilities |
| Pálsdóttir et al. [102]/2024 | Tongue | Physical disabilities | Tongue sensors | TDS | Semi-automated vs. manual | Acc: 90-95%, Enhanced Autonomy | Requires semi-automation configuration |
| Lontis et al. [103]/2021 | Tongue | Tetraplegia | Magnetic sensors (TDS) | TDS | Real-time tongue control | Acc: 93% | Initial learning curve |
| Abbas et al. [104]/2024 | Tongue | Paralyzed and quadriplegic patients | Wireless tongue sensors | TDS | Real-time tongue control | Acc:92% Independence Improved | Limited signal robustness in noisy environments |
| Sahadat et al. [105]/2018 | Tongue | Severe disabilities | Magnetic sensors (TDS) | TDS | Self-directed mobility | Pre: 95% | Requires calibration |

3.7. Previous Work based on Respiration Movements

The respiration-based control method for wheelchairs offers a simple, intuitive solution tailored for individuals with severe motor impairments. Relying solely on natural breathing eliminates the need for specialized training or complex physical inputs, ensuring ease of use and accessibility. Respiration-based wheelchair control systems use sensors like pressure-sensitive masks or nasal cannulas to detect breath patterns, such as short, long, or forceful breaths. Advanced Procedures, such as fuzzy logic or AI, translate these Layouts into precise commands, providing reliable and responsive control. This available root improves the requirement for individuals with modest mobility requiring nominal drive or education, as shown in Fig. 9.

Respiration-based wheelchair control systems use the user's breathing patterns as input signals to direct the wheelchair's movement. This approach typically involves pressure-sensitive masks, airflow sensors, or nasal cannulas that find variations in the operator's breath, like force duration or frequency. These respiration signals are refined and translated into drive commands, exploitation procedures such as an advanced logical system or car acquisition, and representations to set the right actions, care, poignancy, smart turn, or fillet. By mapping specific breathing Layouts to commands, respiration-based control systems provide a hands-free, intuitive Answer for individuals with limited physical mobility, enabling them to control their wheelchairs with ease.

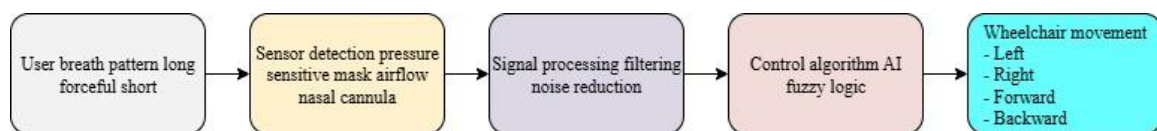


Fig. 9 Respiration-based wheelchair control workflow

Herrera et al. [106] introduced a novel respiration-based control method, which developed a breathing biofeedback system to enhance relaxation for wheelchair users during city navigation, reducing stress and improving comfort and focus in urban environments. González-Cely et al. [25] created a real-time wheelchair control system using POF-based pressure sensors, offering precise and responsive navigation for individuals with physical disabilities. The system showed high reliability and accuracy during user trials. Chia-hung et al. [37] developed an embedded monitoring system with non-invasive sensors to track heart and respiratory rates, enabling continuous health monitoring for wheelchair users without disrupting daily activities.

Cui et al. [107] proposed an intelligent wheelchair adjustment system using action intention recognition and advanced sensors for real-time, adaptive, user-centered mobility solutions. An embedded system for real-time monitoring of cardiorespiratory signals in wheelchair users, enhancing safety and well-being through continuous, as described by Chang et al. [37]. Table 7 compares the previous works based on respiration movement signals.

Table 7 Comparison of previous work based on respiration movement signal

| Ref/Year | Input Signal | Type of Disability | Sensor Type | Input Method | Control Strategy | Performance Metrics | Limitations |
|----------------------------|----------------------------|-----------------------|----------------------------|--|-----------------------------------|----------------------------------|--|
| Herrera [106]/2022 | Breathing patterns | Physical disabilities | Biofeedback sensors | Breathing biofeedback system | Biofeedback-based control | Acc: ~90%, Improved independence | Limited focus on mobility control |
| González-Cely [25]/2021 | Pressure signals | Physical disabilities | POF-based pressure sensors | Real-time pressure detection | Pressure-based wheelchair control | Responsive feedback; Acc: ~91% | Requires precise pressure calibration |
| Chia-hung et al. [37]/2020 | Heart and respiratory rate | Physical disabilities | Embedded biometric sensors | Unobtrusive heart and respiratory monitoring | Smart control | N/A | Focused on health monitoring, not control |
| Cui et al. [107]/2023 | Action intention | Physical disabilities | Action recognition sensors | Action intention recognition | Attitude-based wheelchair control | N/A | High dependency on user intention interpretation |
| Chang et al. [37]/2022 | Cardiorespiratory signals | Physical disabilities | Embedded biometric sensors | Cardiorespiratory monitoring system | Real-time health | N/A | It does not address mobility control directly |

3.8. Previous Work Based on GSR

Integrating GSR with BCI makes the wheelchair control system adaptive to physical commands and emotional cues, creating a more intuitive, responsive, and user-friendly experience for individuals with severe motor impairments, as shown in Fig. 10.

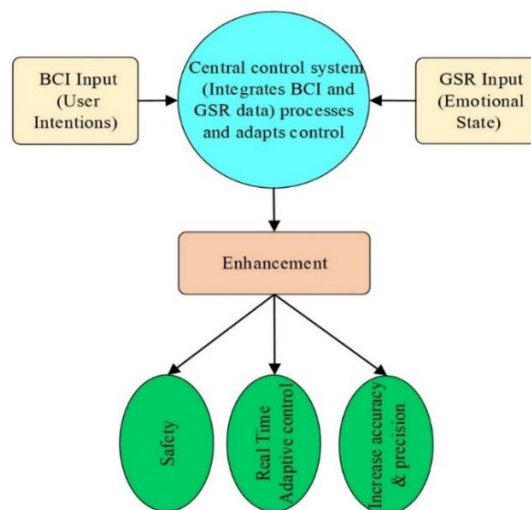


Fig.10 Enhanced wheelchair control through BCI-GSR integration

- (1) Enhanced Safety: GSR enables the system to detect stress, ensuring safer wheelchair operation in potentially overwhelming situations.
- (2) Improved User Experience: Incorporating emotional context from GSR enhances adaptability, providing smoother and less stressful control.
- (3) Higher Precision: Integrating Information from GSR and BCI improves the system's Precision by considering cognitive and emotional states to explain operator needs.

GSR has been combined as a valuable input for enhancing wheelchair control systems by finding emotional and stress levels in Operators. Studies show that GSR signals with different physical information get a dynamically set wheelchair to conduct an exploiter console guard and increase reactivity. By recognizing stress or emotional changes, GSR-based systems enable more adaptive and intuitive wheelchair navigation that caters to operators' psychological and physical needs. Cruz et al. [38] demonstrated that GSR signals could be used to find stressful situations while controlling a robotic wheelchair using a BCI. The study's results successfully showed that GSR might know cathartic states, which would improve the guarding and Adjustability of wheelchair check systems. Gadekar et al. [108] proposed a new generation of wheelchairs sensitive to the emotional behavior of operators. Incorporating cathartic feedback, these systems render the amp further personal and accommodating, enhancing the console and employment for operators with disabilities.

Table 8 Comparison of previous work based on GSR signal

| Ref/Year | Input Signal | Type of Disability | Sensor Type | Input Method | Control Strategy | Performance Metrics | Limitations |
|------------------------------|----------------------------------|--|------------------------------|----------------------------------|--|---------------------|--|
| Cruz et al. [38]/2021 | GSR | Physical disabilities | GSR sensors | Emotion detection in BCI | Stress-adaptive wheelchair control | N/A | Limited to GSR data accuracy in stress detection |
| Gadekar et al. [108]/2025 | Emotional behavior | Emotional regulation and physical disabilities | Emotion-sensitive sensors | Emotion recognition in BCI | Emotion-sensitive wheelchair control | N/A | Requires emotional model adaptation |
| Shafer et al. [109]/2016 | Navigation signals | Physical disabilities | Robotic sensors | Autonomous robotic navigation | Fully autonomous wheelchair control | N/A | Complex in crowded environments |
| Varghese et al. [110]/2021 | IoT and machine learning signals | Emotional regulation needs and Physical disabilities | IoT sensors + ML algorithms | Machine learning-based detection | IoT-driven smart wheelchair control | Acc: ~91% | Dependence on network and infrastructure |
| Siddharth et al. [111]/2019 | Multi-modal bio-signals | Physical disabilities | Wearable bio-sensors | Real-world bio-signal detection | Bio-signal integrated wheelchair control for stress management | N/A | Complex integration in varied environments |
| Perpetuini et al. [112]/2024 | Thermal + GSR signals | Physical & cognitive disabilities | Thermal camera + GSR sensors | Stress/engagement detection | Real-time emotional state monitoring in navigation | Acc: ~93% | Requires fusion of thermal and GSR signals |

Shafer et al. [109] focused on free wheelchair sailing exploitation robotics-based Answers. The study highlighted how robotic technologies can enable independent navigation, reducing the need for external assistance while enhancing mobility for Operators. Varghese et al. [110] considered a calculator-learning-powered smart wheelchair operating within an IoT environment. This unit leverages connectivity and advanced Procedures to render smart sailing real-time adjustments and consolidation with different forward devices for a coherent exploiter to get. Siddharth et al. [111] employed a mature amp wearable multi-modal bio-sensing unit to enable real-world Uses. This system combines multiple physiological Information streams (e.g., heart rate and brain activity) to understand operator needs, ensuring better Adjustability and usability in various assistive technologies, including wheelchairs. Table 8 compares the previous works based on the GSR signal.

Perpetuini et al. [112] presented a novel approach combining real-time thermal and GSR signals to assess stress and engagement levels during manual and autonomous wheelchair control. This hybrid sensing technique improved the accuracy of detecting user states, offering a promising direction for developing emotionally adaptive and context-aware mobility systems. Their work demonstrates that combining multiple physiological indicators can significantly enhance the reliability and responsiveness of assistive wheelchair technology.

3.9. Previous Work Based on Other Signals Controlling Wheelchair

Alternative wheelchair control methods like touchscreens, foot controls, body movements, and send buttons provide accessible options beyond traditional joystick systems. These methods leave individuals with different mobility capabilities to run amputee wheelchairs separately, adjusting the Connections to particular natural abilities. Studies on these approaches highlight their effectiveness in enhancing Operator autonomy, responsiveness, and safety, offering tailored Answers to meet varied Operator needs and preferences.

In the study by Ren et al. [113], a foot-operated control system for wheelchairs using human posture recognition was developed, allowing Operators to navigate through foot movements. This way, in effect, harnesses less limb Reality for check provision, amp hands-free and visceral root for Operators with modest speed trunk mobility. The approach demonstrated high Precision in posture recognition, proving to be a reliable alternative that improves independence for individuals able to control movement through their feet. Majerus et al. [32] developed a sensor-integrated footplate system for powered wheelchairs that detects foot pressure and positioning to support non-invasive and adaptive control. This system provides an accessible solution for users with limited upper-limb functionality and moderate trunk control, using foot pressure inputs to guide movement. Their study demonstrated the potential of foot-based interfaces as alternative control mechanisms for mobility assistance.

Mahmood et al. [114] planned an affordable pass gesture-controlled automatic wheelchair that exploits motion sensors to read pass movements into sailing commands. At the same time, efficiency and affordability are limited to operators with real hand gestures. Patankar et al. [115] developed an IoT-based hand gesture-controlled wheelchair that combines gesture sensors with IoT for real-time navigation. It offers an accommodating check that depends on proper IoT network connectivity for the best operation.

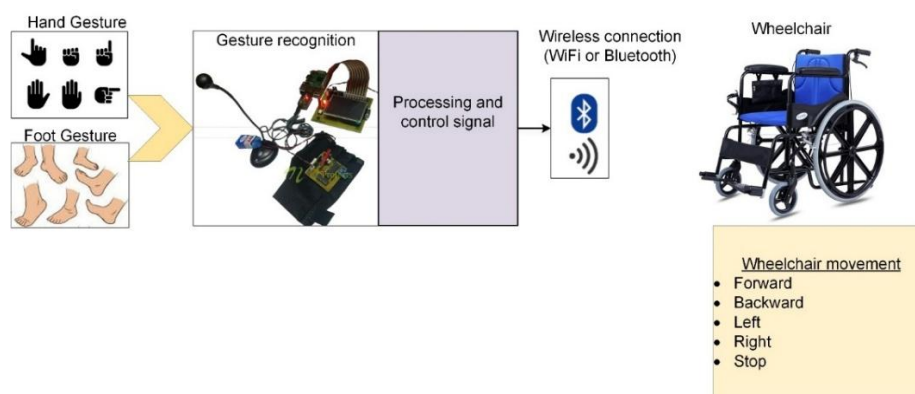


Fig.11 Gesture-controlled wheelchair navigation system

Catalán et al. [29] explained that the AMP standard versatile robotic program was organized to help individuals with variable degrees of impairment. This system allows flexible customization based on the Operator's needs, supporting different control modes and configurations. The standard plan established good inch enhancing availability and Adjustability, devising it as a mobile root for Operators with different natural limitations and nurturing more significant requirements over variable impairment levels. Turnip et al. [100] explored the association in a nursing tense wheelchair check unit, where maturely exploited EMG signals were refined using a backpropagation neural net classifier. This approach utilizes muscle signals to navigate the wheelchair, providing a hands-free Answer for Operators with limited motor control. The EMG-based control, supported by neural network processing, demonstrated high accuracy and responsiveness, showing promise as an effective method for enabling independent mobility in individuals with severe physical impairments.

Makwana et al. [116] developed a touch-controlled wheelchair incorporating a touchscreen interface for navigation. It was tailored for individuals with functional finger or hand control but limited mobility. This system provides an intuitive, user-friendly solution, enhancing autonomy and simplifying wheelchair navigation. Ahmmed et al. [117] introduced a voice-

activated smart wheelchair with ultrasonic sensors for hands-free navigation. The system enables users to control movement through voice commands, while obstacle detection ensures safe operation. This design significantly enhances independence and safety, offering a practical solution for individuals with limited physical abilities. Razy et al. [118] introduced an automated wheelchair featuring dual control through hand gestures and a mobile application. This system provides flexibility, allowing users to navigate intuitively via gestures or remotely using a smartphone, enhancing accessibility for individuals with diverse mobility requirements.

- (1) Hand and foot gesture control systems provide intuitive and adaptable solutions for wheelchair navigation by translating natural movements into commands through specialized sensors.
- (2) Hand Gesture Controls: Using motion or wireless gesture sensors, these systems translate gestures like swipes or pointing into precise commands for movement, such as forward, backward, or turning. By processing inputs in real time, they ensure responsive and intuitive wheelchair operation, allowing for seamless navigation.
- (3) Foot Gesture Controls: These systems rely on pressure or posture sensors to detect foot placement or pressure changes on a footplate and convert them into movement commands. Designed for individuals with functional foot mobility, they enable smooth and natural wheelchair control.

Table 9 Comparison of previous work based on various types of control signals

| Ref/Year | Input Signal | Type of Disability | Sensor Type | Input Method | Control Strategy | Performance Metrics | Limitations |
|----------------------------|------------------------|-----------------------------|-----------------------------|--------------------------------------|---|---------------------|--|
| Ren et al. [113]/2020 | Human posture | Lower limb function | Posture recognition sensors | Foot movement | Real-time posture recognition | N/A | Limited by posture recognition accuracy |
| Majerus et al. [32]/2018 | Foot pressure | Lower limb mobility | Pressure sensors | Foot pressure on the footplate | Real-time position and pressure sensing | N/A | Limited by footplate sensitivity |
| Mahmood et al. [114]/2021 | Hand gestures | Physical disabilities | Gesture sensors | Hand gestures | Gesture-based wheelchair navigation | N/A | Limited to users with functional hand gestures |
| Patankar et al. [115]/2020 | Hand gestures | Physical disabilities | Gesture sensors, IoT | Hand gesture recognition through IoT | IoT-based hand gesture control | Acc.: 92% | Dependent on IoT network stability |
| Catalán et al. [29]/2021 | Modular platform | Modular platform | Various sensors | Configurable (user-specific) | Adaptive modular platform control | N/A | Limited by user-specific configurations |
| Turnip et al. [100]/2021 | EMG | Muscle control for movement | EMG sensors | Muscle contractions | Backpropagation neural network | Acc.: 92% | Dependent on EMG signal strength |
| Makwana et al. [116]/2016 | Touch control | Finger and hand dexterity | Touch sensors | Touchscreen interface | Real-time touchscreen interface | N/A | Limited to touch capabilities |
| Ahmed et al. [117]/2023 | Voice-activated | Limited physical movement | Ultrasonic sensors | Voice commands | Real-time voice recognition | N/A | Dependent on voice clarity |
| Razy et al. [118]/2021 | Gesture and mobile app | Variable motor abilities | Gesture and mobile sensors | Hand gestures and a mobile app | Dual control via real-time app and gestures | Acc.: 93% | Limited by app-device compatibility |

Both methods utilize advanced processors to interpret inputs into movement commands, enhancing accessibility and independence for users with diverse mobility needs. While highly effective, the systems depend on precise gestures or consistent pressure to avoid unintended actions, making them reliable yet user-focused solutions for wheelchair navigation, as described in Fig. 11. Table 9 compares the previous works based on various control signals.

3.10. Comparative Analysis of Biological Signal-Based Control Systems

As smart wheelchair technologies evolve, understanding the trade-offs between different control modalities is essential for selecting the most appropriate system for a user profile and deployment context. Table 10 comprehensively compares major physiological signal-based control systems (EEG, EOG, EMG, voice commands, head movement using IMU sensors, and

hybrid combinations). The comparison is based on key metrics such as strengths, limitations, system complexity, estimated hardware costs, typical accuracy rates, and maintenance requirements.

Table 10 Comparative summary of physiological signal-based control methods for wheelchair systems

| Input Modality | Strengths | Limitations | Complexity | Estimated Cost (USD) | Typical Accuracy | Maintenance |
|------------------------|--|--|------------|------------------------------|------------------|-------------|
| EEG | Captures brain activity; suitable for severe paralysis | Signal noise requires training and calibration | High | \$400–\$1500 (EEG headset) | 75–90% | High |
| EOG | Effective eye direction tracking, non-invasive | Susceptible to lighting changes and drift | Moderate | \$100–\$300 (EOG amplifier) | 80–90% | Moderate |
| EMG | Uses muscle signals; intuitive for moderate mobility | Fatigue and muscle tone variations affect signal quality | Moderate | \$50–\$200 (MYO/electrodes) | 85–95% | Low |
| Voice | Natural interface for those with speech ability | Fails in noisy environments or speech impairments | Low | <\$50 (microphone + module) | 85–90% | Low |
| Head Movement (IMU) | Low-cost, intuitive control using head tilt | Sensitive to external motion artifacts | Low | <\$20 (MPU6050 + controller) | 85–92% | Low |
| Hybrid (EEG+EMG, etc.) | Combining strengths for robustness | Higher cost and integration complexity | Very High | \$300–\$1600+ | 90–98% | High |

Table 10 describes this comparison, reveals that EMG-based and head movement (IMU-based) systems offer the most promising combination of affordability, robust performance, and low maintenance, making them ideal for widespread deployment, especially in resource-constrained settings. In contrast, while offering the highest signal fidelity and accuracy, EEG and hybrid systems suffer from high hardware cost, intensive processing requirements, and greater calibration needs, limiting their practical use in field conditions. Voice-controlled systems remain valuable for users with unimpaired speech but face functional limitations in noisy environments unless paired with robust signal filtering techniques.

From a cost-effective design perspective, using off-the-shelf sensors (e.g., MPU6050, MyoWare, basic microphones) and open-source platforms (Arduino, Raspberry Pi) can reduce system expenses by over 70% while maintaining over 85% classification accuracy in real-time tests. This insight helps guide future system developers toward modular, adaptable, and affordable control architectures tailored to different needs.

4. Comparative Summary and Recommendations

Based on the reviewed modalities, several input methods have been proposed and tested for wheelchair control, each with distinct advantages and limitations depending on the user's condition, environmental factors, and system cost. EEG-based systems offer high flexibility and can detect deep cognitive intent, making them suitable for users with severe motor impairments. However, they require complex preprocessing, are noise-sensitive, and often depend on costly commercial headsets. For example, Cui et al. [22] achieved high classification accuracy using EEG, but noted a significant need for regular recalibration and robust filtering.

EOG-based systems, which detect eye muscle activity, balance signal clarity, and computational requirements. While less invasive than EEG and less complex to process, EOG is more susceptible to signal drift and requires good sensor placement. Studies by Suhaimi et al. [21] and Roy et al. [72] highlighted the advantages of combining EOG with camera vision for object tracking, improving performance in practical tasks. EMG-based systems use muscle signals for command generation. These

are often easier to implement and maintain than EEG/EOG systems, and users adapt quickly. González-Cely et al. [23] showed that EMG signals can be reliably captured using low-cost electrodes with real-time responsiveness. However, EMG may not suit users with limited residual muscle function or fatigue-prone limbs.

Voice command interfaces are highly intuitive and easy to operate, but struggle in noisy environments or with users who have speech impairments. Arshad et al. [24] found voice-based systems effective indoors but unreliable outdoors without noise filtering or redundant modalities. Head movement-based systems, typically employing IMUs or accelerometers, offer a low-cost, responsive, and natural control method. Devices such as the MPU6050 can detect tilt and direction with high responsiveness. Systems developed by Patil et al. [79] and Bui et al. [85] showed that head tilt control systems provided fast response times with minimal training.

Hybrid control systems combine two or more input modalities to overcome the limitations of individual signal sources. These systems have demonstrated superior adaptability in complex environments. For instance, González-Cely et al. [23] (2025) integrated EMG and facial EMG signals, showing higher recognition rates than standalone EMG or voice systems. Similarly, Suhaimi et al. [21] showed that combining eye movement with object detection enhanced the contextual relevance of commands. These results suggest that hybrid systems increase accuracy and provide a more intuitive user experience, especially in scenarios with varying noise levels or lighting conditions.

Intelligent algorithms such as machine learning and fuzzy logic are increasingly used to improve decision-making in real-time wheelchair navigation systems [119]. Fuzzy logic offers rule-based control that is interpretable, computationally efficient, and suitable for embedded systems. On the other hand, machine learning models, such as support vector machines or neural networks, provide higher classification accuracy by learning complex patterns from data. Gopichand et al. [27] reported that integrating machine learning with accelerometer data led to an 87% classification accuracy, outperforming fuzzy systems used by Suhaimi et al. in similar environments. However, fuzzy systems have faster inference times, which is critical for systems requiring immediate responsiveness.

In conclusion, for practical wheelchair deployment, EMG and head movement systems offer high usability at low cost. In contrast, hybrid systems offer the most robust performance when user adaptability is a priority. Integrating open-source platforms like Raspberry Pi and Arduino further enables scalable, affordable, and maintainable designs. These insights will inform the final design recommendation discussed in subsequent sections, as discussed in Table 11.

Table 11 summarizes the strengths and weaknesses of each method in terms of key design criteria

| Input Type | Simplicity | Flexibility | Accuracy | Maintenance | Cost |
|---------------|------------|-------------|-------------|-------------|--------|
| EEG | Low | High | High | Low | High |
| EOG | Medium | Medium | Medium–High | Medium | Medium |
| EMG | High | High | High | High | Low |
| Voice | High | Low–Medium | Medium | High | Low |
| Head Movement | High | Medium–High | Medium–High | High | Low |
| Hybrid | Medium | Very High | Very High | Medium | Medium |

Regarding long-term efficiency and system upkeep, head movement systems using IMUs and EMG-based modalities deliver excellent performance with minimal maintenance requirements [27]. Their stability over time and ease of calibration make them particularly suitable for everyday use without technical support. In contrast, EEG and EOG systems, while powerful in signal richness, often require regular recalibration and are sensitive to environmental noise and signal drift, thus increasing operational demands [22]. Voice-based systems are low-maintenance from a hardware standpoint but may suffer reduced reliability in noisy environments unless augmented with noise-filtering algorithms [21]. EMG and IMU-based systems offer

the most practical combination of efficiency, durability, and low maintenance overhead for users in low-resource or unsupervised contexts. These insights can guide the development of user-centered intelligent wheelchair systems that remain effective over long periods without costly maintenance cycles.

5. Protection Systems for Wheelchairs

Modern electric wheelchairs have increasingly incorporated advanced protection systems to enhance safety, stability, and adaptability. These systems are particularly crucial for individuals with disabilities, as they address various risk factors, such as obstacles, uneven terrain, and sudden environmental changes, ensuring smoother and safer operation. Common protective features include:

Obstacle Detection and Avoidance: Utilizing ultrasonic, infrared, or LIDAR sensors, these systems detect obstacles in the wheelchair's path, automatically adjusting speed or direction to prevent collisions, as shown in Fig. 12 [28, 120].

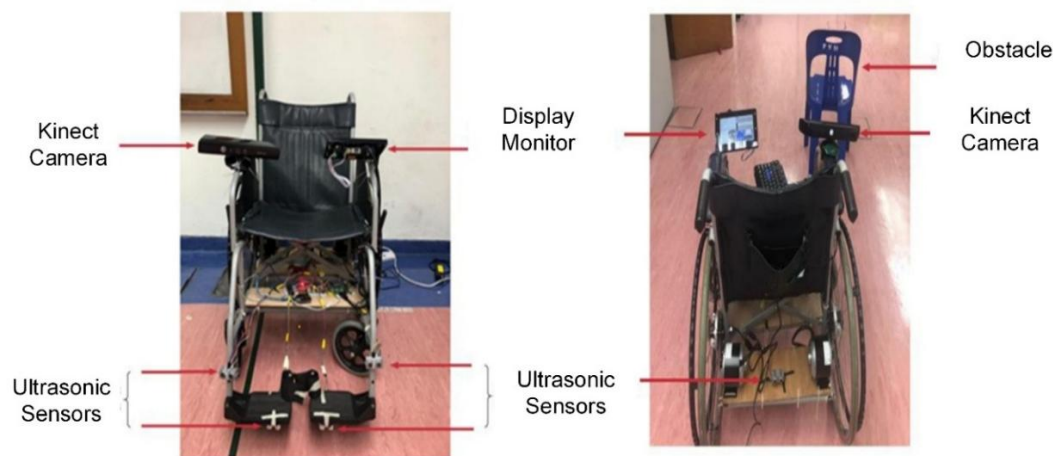


Fig. 12 Front and back views of placing the ultrasonic sensors on the wheelchair [28]

Anti-Tip Mechanisms: Wheelchairs have gyroscopes or accelerometers to monitor tilt and prevent tipping on inclines or uneven surfaces [121].

Speed Regulation Based on Terrain: Advanced sensors assess the surrounding terrain and adjust the wheelchair's speed accordingly, which is particularly useful for outdoor navigation [122].

Fall Detection and Alerts: Some systems automatically incorporate wearable sensors to detect a fall and alert caregivers or emergency contacts [122-123].

Future advancements focus on AI-based predictive analytics, designed to anticipate potential hazards rather than merely react to them proactively. These innovations offer more adaptive and responsive safety measures, enhancing the independence, security, and confidence of wheelchair users while ensuring a safer and more seamless navigation experience.

6. Challenges and Limitations of Wheelchair Control Systems

Based on Selection, a suitable method for controlling a wheelchair requires careful consideration of the individual's needs and abilities, and regular assessments to ensure the technique remains practical and comfortable. Each control method has limitations and should be evaluated to align with the user's capabilities.

6.1. Challenges and Limitations of Wheelchair-Based EEG

Mobile EEG systems for wheelchair control are good examples of newly developed BCIs for mobility control. However, they come face to face with unique problems and inefficiencies. Records obtained from EEG are often distorted with artifacts,

including facial and muscle movements, eye blinks, and other external sources, including vibration or noise produced from the movements of the wheelchair motors [47]. Problems in measuring parameters during the operation of the equipment are exacerbated by motion artifacts [40]. Also, those systems require significantly more attention to be paid to, and using them for long periods results in people becoming either too exhausted or not as efficient as they were when they began. Signal drift further impacts stability, which arises from variations in the contact between the electrodes and the skin. The key hardware limitations are the inconvenience of wearing an EEG cap or electrodes when using the system and integrating additional hardware that can be transported in the wheelchair without being bulky or relying on batteries.

Signal processing is an objective time process, and it is rather challenging to reach high levels of accuracy of classification, particularly between intentional commands and non-intentional movement activity [40]. Some disadvantages familiar to any usability test are a high learning effect, fluctuating calibration requirements [46], and individual variability in EEG signal patterns [49], which suggests the need for individual tuning. Neurological impairments may also make signals untrustworthy in the same way [50].

EMI and irregular surfaces also affect motion artifacts, lowering system reliability and performance. Some ethical and psychological issues include the overdependence on these systems, privacy risks, especially with EEG data risks, and the problem of ensuring people's trust [41]. Costs and ease of access are also important factors, because they are generally complex, and they come with high costs of installation, maintenance, and operation [40]. Addressing these limitations requires multidisciplinary efforts in signal processing, hardware design, ergonomics, and user training to make these systems more effective, accessible, and user-friendly.

6.2. Challenges and Limitations of Voice Recognition

Power wheelchair technology, through a voice recognition system, is a new and most appropriate means of assistive mobility. Nevertheless, they have several important limitations or concerns contributing to problems limiting their use. There is one significant disadvantage: the technical complexity of advanced technologies, further and further, like neuro-fuzzy systems, demands a relatively large amount of computational resources and intricate design techniques [65]. The fourth is limited command recognition, adding that such systems cannot always distinguish between different voice commands and have difficulty differentiating between various commands in realistic conditions [35]. They exhibit poor reliability in noisy environments, and their speech limitations reduce their accessibility for special needs users [26]. Some systems still rely on joystick integration as a fallback mechanism, compromising their independence as a control method [55].

Moreover, most implementations are either working and responsive only for basic or certain specific words, but cannot be incorporated into a sequence of natural speech [56-57]. These issues are compounded by the fact that voice quality de-emphasizes tone, accent, and clarity and significantly affects performance [59]. Interference and low accuracy, particularly in dynamic conditions and especially when background noise is present, also complicate usability problems [58]. However, inadequate training data hinders the flexibility and efficiency of the AI models, suggesting that these systems are not as effective for different users and environments [61]. These limitations are solved by improving noise-handling algorithms, creating adaptive AI systems, and designing user-friendly AI systems for everybody. A multidisciplinary collaboration of AI and systems related to signal processing and human-machine interfaces must be developed to improve the effectiveness, precision, and usability of voice-recognition wheelchair control systems.

6.3. Challenges and Limitations of EOG

While using Electrooculography systems for wheelchair control, various issues arise, making them almost impractical in daily life applications. Their lack of variation in testing the device on different users and the problem of noise interference

make them not very versatile in other conditions [66]. Reliance on user calibration and comfort increases usability problems due to the need for constant adjustments [67]. Massive, complex algorithms required by these systems make them applicable only in simulated environments; however, operation in low-light conditions also significantly hinders these systems [68-69]. As with many immersive systems that rely on six degrees of freedom control, the head has to maintain a stable field of view, which can be a problem for some users.

Current implementations remain primarily at the level of fundamental fascination, that is, demonstrations of applying the system for specific tasks such as grasping or communication, rather than for mobility-oriented tasks [70]. Current implementations often remain at the proof-of-concept stage, focusing on particular tasks such as grasping or communication rather than broader mobility-focused applications [72, 77]. In particular, their dependence on restricted processing capacity and high demands on the amount of training data exacerbate the aforementioned practical application challenges [74-75]. To overcome these limitations, further improvements in the system design, supported hardware systems, and algorithms are needed to make them more robust, efficient, and usable in real-life environments.

6.4. Challenges and Limitations of Head Movement

Head movement-based wheelchair control systems present an innovative approach to assistive mobility but face several challenges and limitations in real-world applications. Such systems might need strict calibration, which limits their applicability and dependability [78, 124]. Calibration needs and limited functionality in detecting diverse head movements restrict their adaptability [79, 82]. Restrictions are placed on wiring arrangements, and the smooth terrains also limit the system's versatility on different terrains [80]. Also, these systems may need an additional power source that limits their utility for mobile or outdoor applications [81]. The processing speed is a further disadvantage when returning results, especially in real-time situations, and if the environment is highly fluid [84].

Furthermore, the mechanism, interaction constraints, and directions deprive such systems of a broad possibility to meet individual user requirements [85-86]. Frequent calibration requirements and adaptations for clinical settings further increase the complexity of implementing these systems [87]. Some systems are constrained to users with specific head movement capabilities, making them less inclusive [39]. Finally, their limited flexibility in handling complex environments underscores the need for advancements in design and adaptability [91]. To overcome these limitations, as mentioned above, better calibration methods, faster computational methods, and modularity of designs will be important in making practical use of these head movement-based control systems.

6.5. Challenges and Limitations of EMG

EMG-based wheelchair control systems offer a promising method for assistive mobility but face several notable challenges and limitations. However, one of them is their reliance on particular user conditions, designed for use only by ALS patients [92]. The complexity of the operation is a drawback to its use since it makes the systems less easy to use compared to the applications/routine tools [93]. In some cases, accuracy means long training, as misinterpretation of signals can cause errors in control [94, 98]. Using muscle signal strength decreases the reliability of these systems to its users who have weak or occasional contractions [95].

Also, in some system implementations, control strategies need modification to suit a specific need, making the systems cumbersome [27]. Some depend on outdated equipment that requires upgrades to meet new-generation technology and the actual situation requirements [96]. High data processing needs also mean increased computation, reducing real-time response [97]. Finally, these systems are often restricted to specific muscle groups, such as forearm mobility, limiting their inclusivity [99]. The elimination of these drawbacks calls for innovations in friendly designs, algorithms' flexibility, and signal processing enhancement for enhanced reliability of electromyography systems for broader use.

6.6. Challenges and Limitations of Tongue Movement Signal

Tongue-movement-based WC is one of the possible ways to achieve assistive mobility, yet it has some significant issues. These systems are typically specific to the face and tongue and, therefore, not very versatile for broader usage [101]. Semi-automation configurations are needed, making the systems more difficult to set up and use [102]. Users may also experience the initial time required to learn and navigate the products or systems before they become useful [103]. Also, these systems do not possess flexibility for non-tongue audiences, limiting the potential audience even more [103]. Keeping the signal stable in noisy environments is still tricky because interference from the outside environment may decrease the reliability [125]. Considerations such as calibration requirements create another level of complication, hence the usability question [105]. Addressing these challenges through improved design, adaptability, and robustness will enhance their effectiveness and usability in real-world scenarios.

6.7. Challenges and Limitations of Respiration Movement Signal

Respiration movement-based wheelchair control systems are an engaging help for mobility-impaired people, yet these have some significant disadvantages. Such systems may be less concerned with mobility control, though other functions like health care may take precedence [106]. It is important to accurately calibrate the signal to pressure, which may pose difficulties in setup and operation [25]. Many implementations are primarily used for health monitoring rather than to control movements, limiting their application in mobility-based systems [37]. Unlike keyword-based approaches, these systems depend on an accurate assessment of the intention of the users, which may be quite problematic in real-time applications [107]. In particular, they often do not provide mobility control as a primary form of control at all, and thus can serve as a poor standalone control mechanism [37]. Improvements in calibration, interpretation accuracy, and a stronger emphasis on mobility control are needed to enhance their usability and reliability in practical applications.

6.8. Challenges and Limitations of GSR

Implementing GSR-based control in a wheelchair has challenges despite its ideal possibilities. These systems are sensitive to the accuracy of GSR data, stressing the reliability of this technique [38]. They still undergo little testing, which leaves knowledge gaps about their roles in real-world situations [112]. The requirement for emotional model adaptation introduces an additional challenge – the system must distinguish between different stress signals [108]. Such stressful signals are problematic in other conditions caused by population density due to the system's inability to filter out such signals from the environment [109]. Third, reliance on the network infrastructure can limit the applicability of devices in several locations where such networks are not as accessible [110]. Complex integration in varied environments further limits the scalability and adaptability of these systems [111]. Five modifications were suggested for future work to increase GSR data interpretation, real-world testing of GSR technology, and minimize external modem usage.

6.9. Challenges and Limitations of Other Signals Wheelchair Control Methods

Other input signals for the control of wheelchairs provide new solutions but have specific problems and restrictions. Posture-based human form systems are conditioned with posture recognition accuracy, which makes them inappropriate for complicated movements [113]. Foot pressure and gesture systems are constrained by the footplate sensing capability and the inability to interact with users with minor mobility differences or adjusted footrests [32, 91]. Hand gesture systems are based on functional hand gestures, and IoT network connectivity and quality hamper real-time reaction time [114]. Joystick controls have problems with grip and delicateness of touch, and demand upper limb function, excluding patients with severe mobility impairment or tremors [126-127]. Modular platforms have issues with choices because of personal configurations, which limit flexibility [29].

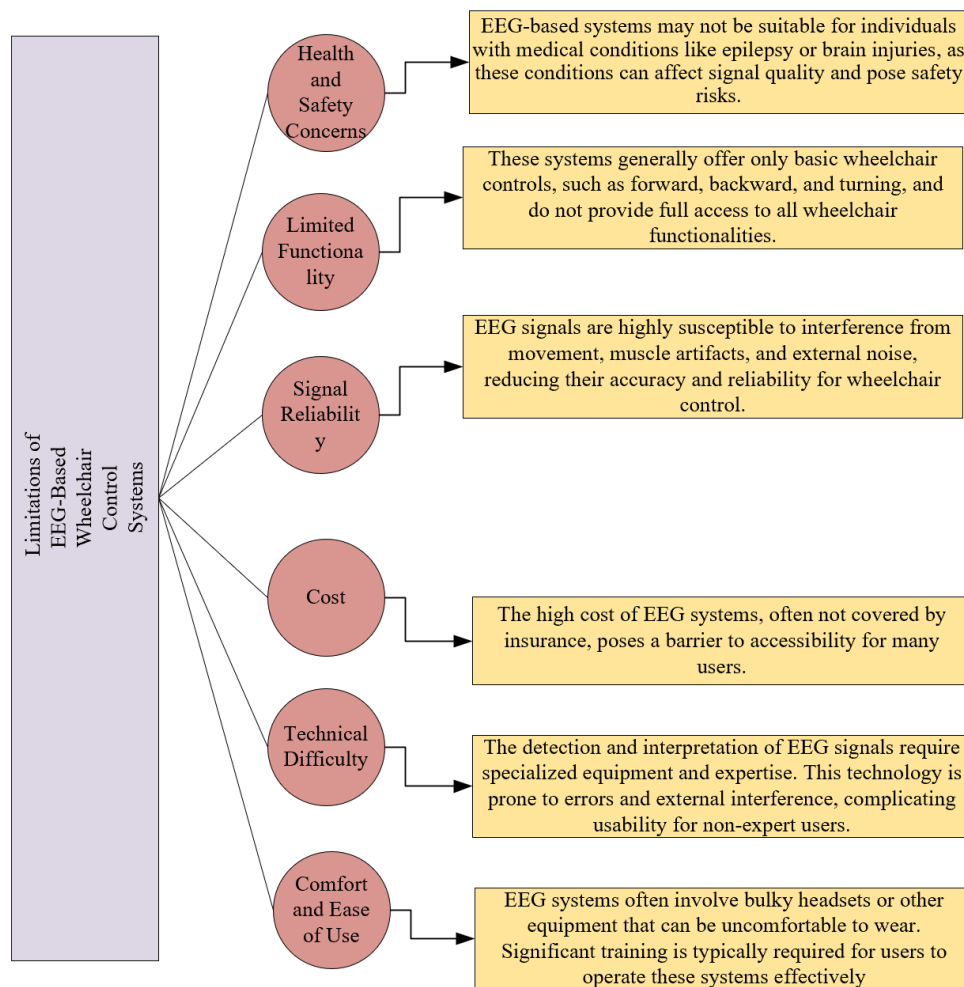


Fig. 13 Limitations of EEG-based wheelchair control systems

Some problems of electromyography-based systems are indicated by the reliance of such systems on the strength of the EMG signals detected or the range of mobility of the patient's neck, as in the case of Cervical Movement Systems [100]. Touch control systems struggle in harsh environments and are challenging for users with limited dexterity, prone to accidental inputs [116]. Voice-activated systems are somewhat limited because they depend on voice quality: they cannot work well in loud surroundings or with people who have speech difficulties [117]. App-device compatibility restricts gesture and mobile app control systems, making it difficult for applications to work seamlessly [118]. Solving these problems necessitates further development in recognition technologies, better flexibility, and an orientation toward the user to make these systems more reliable and friendlier to all users.

Furthermore, systems that employ physiological signals, such as EMG or EEG, encounter distinct challenges, including signal noise, the necessity for precise sensor placement, prolonged training durations, and the substantial costs associated with advanced technology, all of which can impact the efficacy of assistive systems. Consistently assessing user experiences and modifying control mechanisms can alleviate these problems, assuring the preservation of both accessibility and functionality, including the following:

- (1) **Signal reliability:** The accuracy and reliability of the physiological signals used to control the wheelchair may vary depending on the individual's specific abilities and conditions. Sometimes, signals may be weak, inconsistent, or easily affected by external factors.
- (2) **Technical difficulty:** The technology required to detect and interpret physiological signals can be complex and challenging to set up, especially for individuals with limited technical expertise.
- (3) **Cost - Physiological signal-based control systems** can be expensive and not covered by insurance or other funding sources.

- (4) Comfort and ease of use: Some physiological signal-based control systems can be uncomfortable or cumbersome and may require special training and practice to use effectively.
- (5) Availability: Physiological signal-based control systems may not be widely available, especially in rural or underserved areas, and may not be compatible with all wheelchairs.
- (6) Limited functionality: Physiological signal-based control systems may not provide the same functionality and control as other methods, such as joystick or touchpad control.

Addressing these challenges through technological advancements, improved training programs, and cost-effective solutions will make EEG and EOG-based wheelchair control systems more practical and accessible. Below is a summary of the limitations and disadvantages of these systems, as discussed and shown in Figs. 13 and 14.

While EEG and EOG-based control systems offer promising solutions for individuals with severe disabilities, their limitations—such as reliability, cost, technical difficulty, and restricted functionality must be addressed to broaden their accessibility and effectiveness. Advancements in technology, combined with cost-reduction strategies and improved usability, are critical to overcoming these challenges and making these systems more inclusive and practical for real-world use.

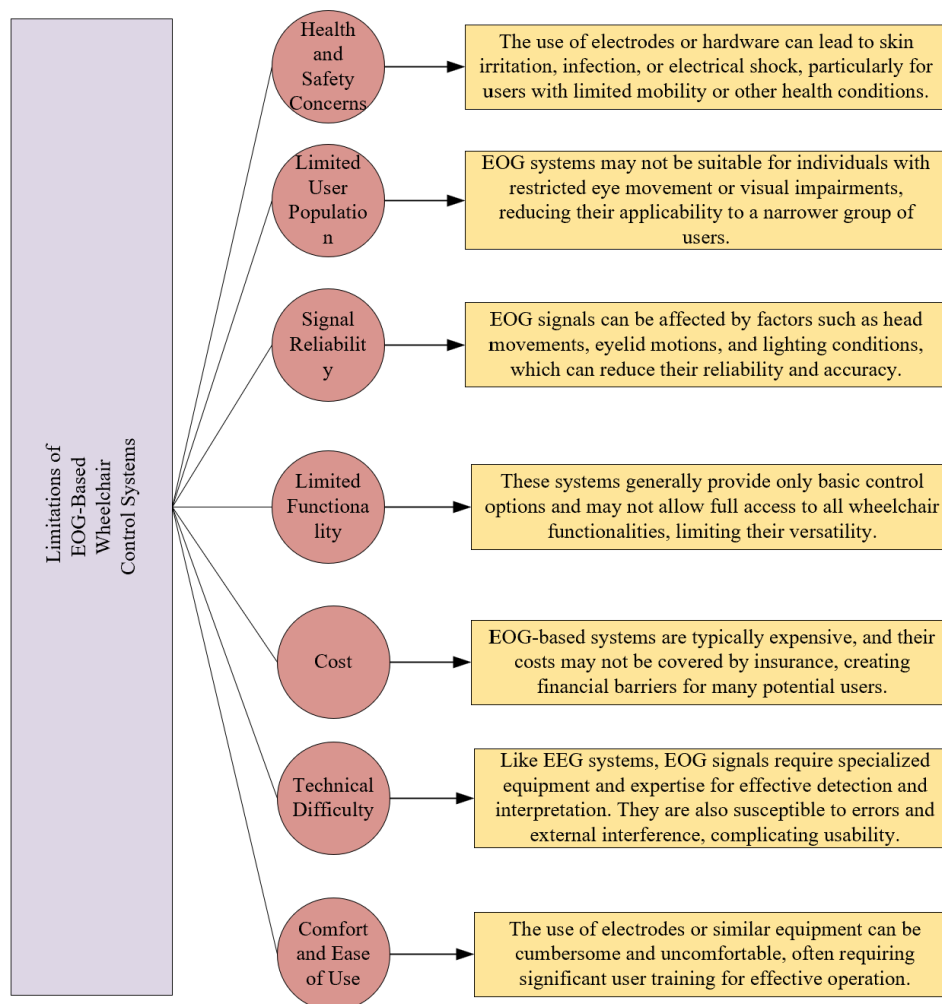


Fig. 14 Limitations of EOG-based wheelchair control systems

7. Advantages of wheelchair control methods

Several input control strategies have been adopted in modern wheelchair systems to support mobility and autonomy for individuals with motor impairments. Table 12 presents a comparative summary of their key advantages, focusing on usability, invasiveness, functionality, and quality-of-life improvements.

Table 12 Comparative advantages of wheelchair control methods

| Control Method | Key Advantages |
|---------------------|--|
| Vision-Based | <ol style="list-style-type: none"> (1) Intuitive and natural interface using eye gaze or head direction. (2) Requires minimal physical effort or training. (3) Customizable UI for diverse impairments. (4) Supports interaction with other devices (smartphones, PCs). (5) Enhances mobility and autonomy in both indoor and outdoor spaces. |
| Head Movement-Based | <ol style="list-style-type: none"> (1) Simple directional commands using head tilts or nods (2) Cost-effective solution using IMU or accelerometers (3) Comfortable and wearable (non-invasive). (4) Enables multi-function control, including smart devices. (5) Improves confidence and ease of movement in daily life. |
| Voice-Controlled | <ol style="list-style-type: none"> (1) Natural communication channel using speech. (2) No physical contact or sensor wear required. (3) Ideal for users with limited limb mobility. (4) Integrates well with smart environments and home automation. (5) Promotes verbal interaction and independence. |
| EEG/EMG-Based | <ol style="list-style-type: none"> (1) Captures brain or muscle intent accurately for command generation. (2) Suitable for severe motor impairments. (3) Non-invasive surface electrodes were used. (4) Enables precise and reliable control with training. (5) Potential to operate multiple assistive technologies. |
| EOG-Based | <ol style="list-style-type: none"> (1) Utilizes eye movement signals for directional control. (2) Highly intuitive and quick to learn. (3) Non-invasive and comfortable to use. (4) Effective for users with partial or full limb paralysis, (5) Enhances control accuracy through deliberate eye shifts. |

8. Discussion

The field of wheelchair control systems has advanced significantly, incorporating diverse input modalities to address the unique needs of individuals with varying disabilities. These include BCI systems using EEG signals, EOG for eye movement tracking, voice recognition, head movement detection, and respiration-based control methods. Each signal presents its strengths and limitations, making it essential to align the chosen control method with the patient's specific situation, requirements, and budget. Thus, based on the data derived from EEG measurements, BCI systems provide a signal opportunity for persons with severe disabilities and enablers of a direct brain-computer interface. However, it is expensive for many clients due to their high costs, sensitivity to signal interferences, and inability to work without user training. Likewise, voice recognition affords customers an equally convenient and often one-handed approach, especially to users who have lost or have not entirely lost control over their hands but are also hampered by noise and speech quality restrictions.

EOG-based systems can be controlled through eye movements. As such, they would be ideal for individuals with limited physical mobility but require frequent calibration and are inefficient in dynamically varying environments. Red light and turn signal indicator technologies, utilizing accelerometers and gyroscopes, are suitable for people with sufficient neck motion but have outdoor deployment issues and constantly require recalibration. However, such respiratory-based systems, which can provisionally control wheelchairs depending upon the user's breathing patterns, are exclusively devised for those without communication. However, they focus mainly on health management, not raw mobility.

Due to the variation in user requirements, none of the control signals can be considered the most effective. However, a particular control method should be manageable with the essential patient characteristics such as motor skills, local conditions, and costs. For this reason, multicomponent hybrid systems that utilize several signals simultaneously, for instance, EEG with EOG or voice with head motion detection systems, are more viable. These multi-modal systems improve the system's accuracy while improving the system's flexibility, since another signal replaces the limitations of one signal. For instance, when one

signal becomes unreliable due to environmental factors or user conditions, the system can rely on alternative input signals, ensuring continuous and effective operation.

Besides flexibility, multiple control signals increase performance parameters, including accuracy, response time, and customer satisfaction. The use of AI and machine learning within a hybrid system makes it possible to make decisions in real time; thus, the system can change its parameters depending on changes in the user's condition or the environment as a whole. Most enhance the wheelchair's general performance and make the user's experience more personal.

Furthermore, there is a cooperation in using multiple signals as control inputs to align with developing user-oriented designs that approach the individual customer's interests. There are situations when one form of control turns out to be insufficient, which is why hybrid systems allow for developing systems with multiple control methods that allow for reliable additional protection in the necessary amount, for example, for safe military purposes. These systems also enable users to experience more personal control since individuals who need these systems have different demands that can be met in the context of adaptable and personalized control configurations.

EEG and EMG signals are highly susceptible to noise, which can arise from motion artifacts, external electromagnetic interference, electrode displacement, or physiological cross-talk. Several studies have adopted techniques such as adaptive filtering (e.g., band-pass or notch filters), Independent Component Analysis, and ensemble averaging to ensure signal integrity and reduce false positives. For instance, EEG systems commonly use preprocessing pipelines to remove ocular and muscle artifacts, while EMG systems may employ root mean square normalization or signal segmentation to improve robustness. Some hybrid control frameworks also integrate confidence scoring or redundancy across modalities to enhance decision reliability. These practices ensure dependable operation in real-time wheelchair control systems, especially in uncontrolled environments.

Although many reviewed systems demonstrate promising performance under controlled laboratory conditions, there remains a significant gap in validating their robustness in real-world scenarios. Environmental variability—such as dynamic lighting, ambient noise, motion artifacts, and user-specific behavior—can significantly influence system reliability and responsiveness. Therefore, future studies should emphasize real-environment trials to assess usability, safety, and performance consistency across diverse conditions. Such validations ensure successful deployment and user adoption in practical daily life contexts.

To sum up, the evolution of wheelchair control systems is discussed, and the relationships between the choice of the controlling method and the state of the patient, his or her needs, and the cost constraints are identified. No single signal is superior to the others. However, combining multiple signals creates a hybrid control system that yields flexibility, robustness, and other performance parameters such as accuracy and speed. These systems can enhance the life experience of consumers with disabilities if current shortcomings are addressed and the emphasis is on tailor-made solutions, providing them with more prosperous opportunities for successful maneuvering in various daily life scenarios.

9. Conclusions

This review systematically examined the current landscape of electric wheelchair control systems based on physiological signals, including EMG, EEG, EOG, voice, and head-movement detection. The analysis assessed their operational capabilities, cost considerations, adaptability, and potential to enhance independent mobility for individuals with severe motor impairments. The main conclusions are as follows:

- (1) **Simplicity and Flexibility:** EMG and voice-controlled systems offer straightforward interfaces and are suitable for users with partial motor function. EMG provides good accuracy with intuitive operation, while voice commands enable hands-free control when speech is intact. EEG and EOG approaches increase flexibility for users with more severe impairments but require complex calibration and setup.

- (2) **Low-Cost Design Potential:** Affordable, high-performing solutions can be developed using accessible hardware such as MPU6050 sensors, Raspberry Pi, and Arduino platforms. These components allow hybrid configurations that balance performance and affordability, making them feasible for low-resource environments.
- (3) **Efficiency and Low Maintenance:** Head-motion and EMG systems demonstrate lower maintenance needs and greater reliability over time. Unlike EEG and EOG devices, which often require frequent recalibration due to signal drift, these simpler systems remain stable across diverse environments.
- (4) **User-Centric Implications:** The effectiveness of each approach depends on individual user profiles. Personalized calibration, adaptive control algorithms, and tailored training are critical to achieving consistent performance and user satisfaction.
- (5) **Future Research Directions:** Future research should prioritize multimodal and adaptive systems capable of switching between input signals in real time based on user intention and environmental conditions. Emphasis should be placed on reducing training time, improving robustness, and leveraging open-source tools to lower costs.

In summary, intelligent, affordable, and user-centered wheelchair control systems have strong potential to improve mobility and independence. Continued interdisciplinary collaboration is essential to translate these technologies into practical, widely adopted solutions.

Conflicts of Interest

The authors declare no conflict of interest.

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