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Evolution of Wheelchair Technology: A Comprehensive Overview of History, Disabilities, Types and Control Mechanisms

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A B S T R A C T

For individuals with severe disabilities, wheelchairs serve as vital tools for enabling movement and participation in society. This review explores the history of wheelchair development, from its inception in ancient civilizations to modern technological advancements, highlighting the impact of these innovations on accessibility and quality of life. The paper also examines the various diseases and conditions that necessitate wheelchair use, such as spinal cord injuries, cerebral palsy, muscular dystrophy, and multiple sclerosis, emphasizing their prevalence and societal implications. In addition, the review delves into advancements in wheelchair design, including manual and electric models, smart wheelchairs with integrated artificial intelligence, and specialized chairs that assist with standing or reclining. By addressing barriers such as affordability, accessibility, and inclusivity, this paper underscores the importance of integrating technological innovation with policy reforms and psychological support to enhance the lives of individuals reliant on wheelchairs. Through a comprehensive analysis, this study aims to inspire future efforts to improve mobility solutions, fostering greater independence, inclusion, and equity for people with disabilities worldwide.

1. Introduction

Mobility is not just a matter of convenience; it is a fundamental aspect of human dignity, independence, and participation in society. For individuals with severe physical disabilities, the inability to move freely creates significant barriers that extend beyond physical limitations, impacting mental health, social inclusion, education, and employment opportunities. According to the World Health Organization (WHO), over 75 million people globally require a wheelchair, yet only a fraction has access to appropriate mobility devices due to socioeconomic barriers, inadequate infrastructure, and societal stigma [1]. This gap highlights the urgent need for innovative solutions that not only provide mobility but also foster a sense of belonging and empowerment. The psychological impact of mobility impairment is profound, particularly for children and adults who experience isolation or marginalization. Studies indicate that individuals with disabilities are at higher risk for depression and anxiety, which further hinders their ability to engage in societal activities [2]. Addressing these challenges requires a holistic approach that combines advanced mobility technologies, such as smart wheelchairs, with psychological support and inclusive societal practices. For instance, the WHO emphasizes the need for comprehensive rehabilitation programs that integrate assistive technology with counseling and peer support to build confidence and resilience among individuals with disabilities [3]. Moreover, the societal impact of empowering people with disabilities extends beyond the individual. Accessible mobility solutions not only improve the quality of life for users but also contribute to the economy by enabling greater participation in the workforce. According to the International Labor Organization (ILO), inclusive employment practices could increase global GDP by up to 7% if barriers to workforce entry for people with disabilities are removed [4]. This underscores the potential societal and economic benefits of investing in assistive mobility technologies and fostering inclusive environments. This review explores the historical landscape of the wheelchair through the ages, the diseases that lead to severe disability, and wheelchair technologies designed for individuals with severe disabilities.

2.History

2.1. Early Concepts of Mobility

The history of mobility aids predates the dedicated invention of wheelchairs, with early concepts rooted in adaptations of existing tools. As early as the 6th to 4th centuries BCE, the Chinese developed the wheelbarrow, which likely served as a transport aid for disabled individuals. These early wheeled devices were not designed specifically for human mobility but laid the groundwork for future innovations in mobility aids, emphasizing functionality over form. The use of wheeled tools in ancient China set the foundation for an evolving understanding of assistive devices [5]. At figure1 these primitive wheeled devices, while not explicitly created for the disabled, marked an early understanding of the utility of wheels in overcoming mobility challenges. Similar devices were also found in ancient Greece and Rome, where chariots and carts were adapted for transporting individuals with physical impairments [6].

2.2. Medieval and Renaissance Developments

By the 12th century, Europe saw the introduction of wheeled furniture, which likely inspired rudimentary mobility aids. During the Middle Ages, the use of wheeled furniture in monasteries and royal courts hinted at the possibility of creating mobility solutions for disabled individuals. These early designs, however, were rudimentary and often did not prioritize user comfort or mobility. The first significant step toward the development of a functional wheelchair occurred in 1655, when German watchmaker Stephan Farfel designed a self-propelled chair with three wheels. This innovation marked a turning point, as it allowed users to move the chair independently using a rotary handle. Farfler's design was revolutionary in that it offered an early glimpse into the concept of self-propulsion for mobility aids, an idea that would become central to future wheelchair [7]. Farfler's invention remained a novelty for some time, but it played a crucial role in shifting the design of mobility aids from simple transportation devices to more personalized, user-oriented solutions. This shift paved the way for further innovations during the 18th century [8].

Fig. 1: Represents early wheeled devices used in ancient China and Europe, which may have been adapted to aid individuals with disabilities.

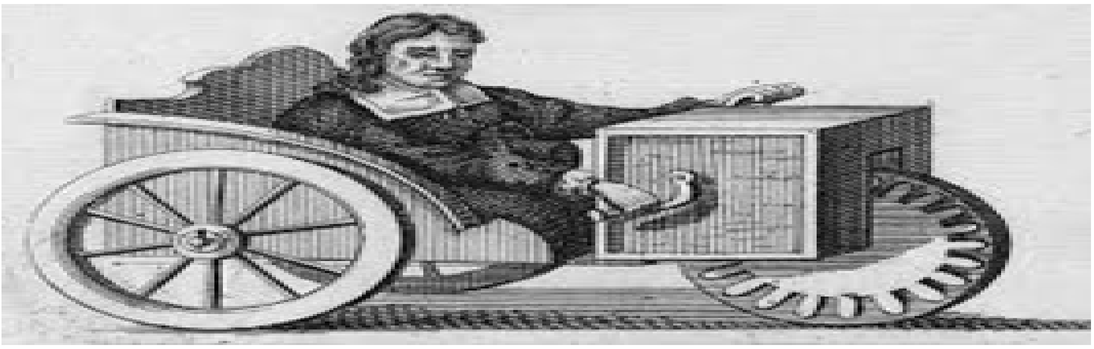

Fig. 2: Depicts Stephan Farfler's invention in 1655, the first self-propelled wheelchair with three wheels, allowing users to move it independently using a rotary handle.

2.3. 18th to 19th Century Innovations

In the 18th century, the commercialization of wheelchairs began. These devices started appearing in medical catalogs, often with ornate designs resembling armchairs, indicating a growing awareness of both function and form in the design of mobility aids. One of the most notable innovations was James Heath's "bath chair," introduced in 1760. The bath chair was designed to aid the mobility of invalids, particularly women, by providing a more comfortable and accessible way to move [9]. The 19th century saw significant advancements in materials and manufacturing processes, which led to lighter and more functional designs. The increased use of metal frames, lighter wood, and rubber tires made wheelchairs more accessible to the broader population. Additionally, the industrial revolution contributed to the mass production of wheelchairs, making them more affordable and widespread [10].

Fig.3: Shows the 18th-century "bath chairs," designed for comfort and mobility, particularly for invalids and women, marking an early focus on user comfort.

2.4. 20th Century Milestones

The 20th century was a pivotal period for wheelchair development. In 1932, Harry Jennings invented the first folding wheelchair for his friend, enabling greater portability and ease of use. This innovation revolutionized wheelchair design, as it allowed users to store and transport the device more easily, facilitating its integration into daily life [11].

Fig. 4: Highlights Harry Jennings' 1932 invention of the folding wheelchair, which improved portability and storage.

Post-World War II, Canadian inventor George Klein developed the first electric wheelchair, which integrated a motor to assist with mobility. This invention was particularly significant for injured war veterans, providing them with greater independence. The electric wheelchair marked a major step forward in wheelchair technology, offering users the ability to move without physical exertion [12]. figure5 shown George Klein's post-World War II electric wheelchair, designed to aid injured veterans and provide greater independence. These advancements were vital in increasing the accessibility of mobility aids, leading to asurge in their adoption among people with disabilities.

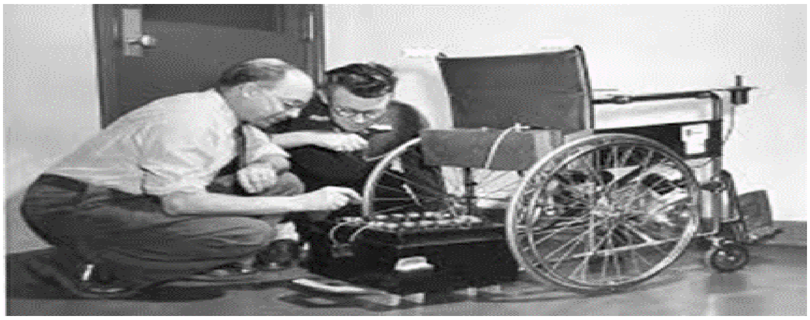

Fig. 5: Features George Klein's post-World War II electric wheelchair.

2.5. Modern Wheelchair Innovations

From the 1980s onward, wheelchair technology saw a surge in specialization. Sports wheelchairs, designed for speed and agility, were developed, enabling athletes with disabilities to compete at the highest levels. Additionally, power-assisted models, such as the push-rim activated power-assisted wheelchair (PAPAW), combined manual and electric technologies to improve user experience [13].

Fig. 6: Illustrates the development of specialized sports wheelchairs, introduced in the 1980s, enabling athletes with disabilities to compete.

The latest innovations in wheelchair technology involve the integration of robotics and artificial intelligence. Brain-controlled wheelchairs, which use neural signals to control movement, represent the cutting edge of assistive technology. These devices are enabling people with severe disabilities, such as paralysis, to regain a level of independence and mobility that was previously thought impossible [14].

Fig. 7: Showcases the latest advancements, such as brain-controlled wheelchairs that use neural signals for movement, representing cutting-edge assistive technology [14].

3. Diseases Requiring Wheelchair Assistance

Wheelchair use is often necessitated by a variety of medical conditions that impair mobility. These conditions may result from injury, degenerative diseases, or congenital disorders, and they significantly affect the quality of life of patients.

3.1. Spinal Cord Injuries (SCI)

Spinal cord injuries are among the most common causes of wheelchair dependency worldwide. These injuries result from trauma to the spine, such as motor vehicle accidents, falls, sports injuries, or acts of violence. Depending on the level of the injury, individuals may experience:

- Paraplegia, which affects the lower limbs and torso, usually resulting from injuries below the thoracic spine.
- Quadriplegia (Tetraplegia), which impacts all four limbs and the torso, occurring due to cervical spine injuries.

The secondary effects of SCI, such as chronic pain, spasticity, and pressure ulcers, further complicate patient mobility and quality of life. Early surgical interventions, such as decompression, combined with long-term rehabilitation, are critical in managing these injuries. Advances in assistive technologies, including powered wheelchairs and exoskeletons, have improved independence for SCI patients [15]. Approximately 250,000 to 500,000 new cases of spinal cord injury occur each year globally. Motor vehicle accidents are the leading cause, followed by falls, acts of violence, and sports injuries. Many of these injuries result in permanent mobility impairments, necessitating wheelchair use for up to 90% of patients with severe injuries. In the United States, the prevalence of SCI is estimated at 294,000 individuals, with males accounting for nearly 78% of cases [16].

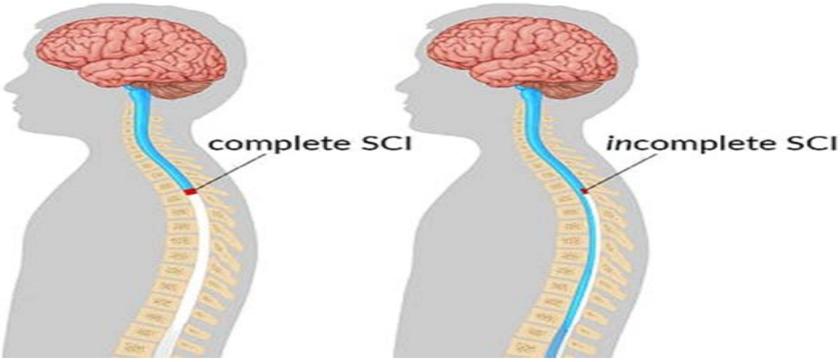

Fig. 8. Illustrates complete and incomplete spinal cord injury.

3.2. Multiple Sclerosis (MS)

Multiple sclerosis is a chronic, immune-mediated disease that damages the central nervous system. Demyelination disrupts the transmission of nerve impulses, leading to muscle weakness, fatigue, spasticity, and impaired balance and coordination. MS progresses in a relapsing-remitting or primary progressive form, with advanced stages often leading to significant mobility challenges. Wheelchair dependency becomes common as the disease worsens, particularly in individuals with long-standing MS. Rehabilitation strategies, including physiotherapy, occupational therapy, and the use of assistive devices, aim to delay wheelchair dependency and enhance independence [17]. Multiple sclerosis affects over 2.8 million people worldwide, with higher prevalence in Europe and North America. About 50-75% of individuals with advanced MS require mobility aids, and nearly one-third eventually rely on wheelchairs. The disease is most commonly diagnosed in young adults aged 20–40 years, significantly affecting their long-term mobility and independence [18].

3.3. Cerebral Palsy (CP)

Cerebral palsy, a non-progressive motor disability, is caused by abnormal brain development or injury to the developing brain. It manifests as spasticity, ataxia, and impaired motor coordination, with severity ranging from mild to severe. Patients with severe cerebral palsy often rely on wheelchairs for mobility due to extensive muscle stiffness and joint deformities. Surgical procedures to reduce spasticity, alongside assistive devices such as specialized wheelchairs, can significantly improve quality of life. Moreover, ongoing research into advanced robotics and neural interfaces offers hope for better mobility outcomes for individuals with CP [19]. It has a global prevalence of approximately 17 million individuals, making it the most common motor disability in children. Around 30% of people with CP rely on wheelchairs for mobility, with the percentage increasing for those with severe forms of the condition. In high-income countries, early interventions and assistive technologies have improved mobility outcomes [20].

3.4. Muscular Dystrophies (MD)

Muscular dystrophies represent a group of genetic disorders characterized by progressive muscle degeneration and weakness. Duchenne muscular dystrophy (DMD), the most common form, leads to loss of ambulation by adolescence. The disease primarily affects boys due to its X-linked recessive inheritance pattern. Wheelchairs are essential for mobility as muscle wasting progresses. Recent advancements in gene therapy, corticosteroid treatments, and supportive care have improved life expectancy and delayed the onset of severe mobility impairments in MD patients [21]. It affects approximately 1 in 5,000 male births worldwide. In the United States alone, around 15,000 individuals live with Duchenne and Becker muscular dystrophy, with most requiring wheelchairs by their teenage years. Advances in therapies are extending life expectancy, but mobility impairments remain a significant challenge [22].

3.5. Amyotrophic Lateral Sclerosis (ALS)

ALS, a neurodegenerative disease, affects motor neurons, leading to progressive muscle weakness, paralysis, and eventual respiratory failure. Early symptoms include difficulty walking, muscle cramps, and slurred speech, progressing to complete loss of motor control. Wheelchair use becomes necessary as the disease advances, with specialized wheelchairs often required to accommodate respiratory devices [23]. Multidisciplinary care, including physical therapy, palliative care, and assistive technologies, plays a crucial role in managing the condition and maintaining patient dignity. ALS has a global incidence of 1–2 cases per 100,000 people annually, with a prevalence of approximately 200,000 individuals worldwide. By the late stages of the disease, nearly all patients require wheelchairs due to severe muscle weakness and paralysis. ALS primarily affects individuals aged 55–75 years and has a significant impact on quality of life and mobility [24].

3.6. Osteogénesis Imperfecta (OI)

Osteogenesis imperfecta, also known as brittle bone disease, is a genetic disorder characterized by fragile bones that fracture easily. Severe forms of OI lead to recurrent fractures, deformities, and impaired mobility. In many cases, wheelchair use becomes essential to reduce fracture risk and enable mobility. Treatments include bisphosphonates to strengthen bones, orthopedic surgery, and the use of custom-designed wheelchairs to prevent further injuries [25]. Osteogenesis imperfecta, though rare, affects around 1 in 10,000 to 20,000 births globally. Severe forms of OI lead to wheelchair use in a significant proportion of patients due to recurrent fractures and bone deformities. Early diagnosis and customized wheelchairs are essential to maintaining mobility and preventing complications [26].

3.7. Parkinson's Disease

Parkinson's disease is a progressive neurodegenerative disorder that impairs motor function due to the loss of dopamine-producing neurons in the brain. Symptoms include bradykinesia (slowness of movement), rigidity, and postural instability, which severely affect gait and balance. In advanced stages, wheelchair use becomes necessary for safety and mobility. Deep brain stimulation and advancements in drug therapies have shown promise in managing motor symptoms and delaying wheelchair dependency [27]. It affects over 10 million people worldwide, with the prevalence increasing with age. By the advanced stages of the disease, approximately 20-40% of individuals require wheelchairs for mobility due to severe motor impairments and postural instability. The global burden of Parkinson's disease is projected to double by 2040 due to aging populations [28].

3.8. Stroke

Stroke is a major cause of long-term disability, often resulting in hemiplegia or general muscle weakness. Depending on the severity of the stroke and the rehabilitation provided, individuals may experience significant mobility challenges. Wheelchair use is often essential for individuals with severe motor impairments or poor balance. Intensive rehabilitation programs, including physiotherapy and occupational therapy, are crucial in maximizing recovery and reducing dependence on wheelchairs. Stroke is a leading cause of disability, with 12.2 million new cases occurring annually and a global prevalence of over 100 million survivors. Of these, approximately 50-60% experience mobility challenges, and around 30% require long-term use of wheelchairs. The burden is highest in low- and middle-income countries, where access to rehabilitation services is limited [29].

3.9. Arthritis

Severe arthritis, including rheumatoid arthritis and advanced osteoarthritis, can lead to joint deformities and pain that impair mobility. The hips, knees, and spine are most commonly affected. Wheelchair use becomes necessary in advanced cases where mobility aids, such as walkers, are insufficient. Surgical interventions, such as joint replacement, can restore some degree of mobility in selected cases [30]. Rheumatoid arthritis and osteoarthritis collectively affect over 595 million people worldwide. Severe arthritis leads to wheelchair dependency, particularly when hip and knee joints are severely damaged. With the global aging population, the prevalence of arthritis-related mobility impairments is expected to rise significantly [31].

3.10. Obesity and Related Conditions

Severe obesity can impair mobility due to joint stress, fatigue, and associated conditions such as diabetes and cardiovascular disease. Wheelchairs are often used to improve quality of life and reduce the physical strain associated with walking or standing for extended periods. Addressing underlying causes, including weight loss and management of comorbid conditions, remains essential for improving mobility outcomes [32]. Obesity affects over 650 million adults and 340 million children worldwide. Severe obesity and its complications, such as joint damage, cardiovascular disease, and diabetes, lead to mobility impairments in a significant number of individuals. It is estimated that 5-10% of individuals with morbid obesity rely on wheelchairs for mobility assistance [33].

4. Standard Dimensions of Wheelchair

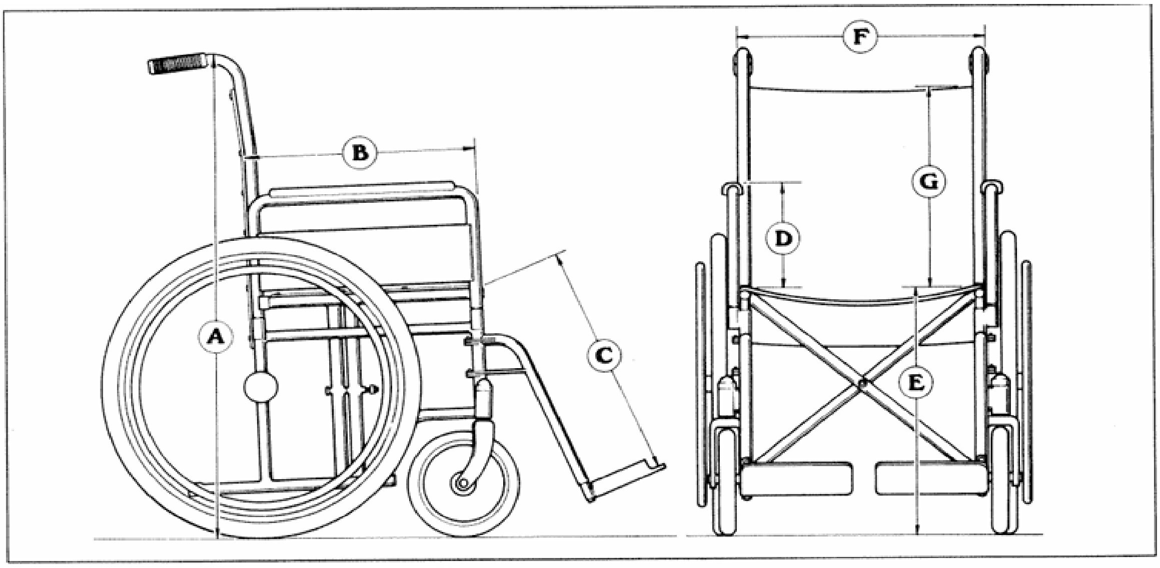

Fig.9. Standard dimensions for adult wheelchairs are as follows [34][35][36]:

Standard dimensions to ensure comfort, functionality, and accessibility. While specific measurements can vary among manufacturers, Fig.9.

a) Overall Height: Approximately 91.4 cm (36 inches)
b) Seat Depth: Standard seat depths range from 40.6 cm to 43.2 cm (16 to 17 inches)
c) Footrest Support (Adjustment Range): The distance between the seat and footrest typically ranges from 41.9 cm to 55.9 cm (16.5 to 22 inches)
d) Armrest Height from Seat Rail (Adjustment Range): armrest heights can vary, but the common range is from 12.7 cm to 30.5 cm (5 to 12 inches)
e) Seat Height from Floor: Standard seat heights are around 49.5 cm
f) Seat and Back Width: Seat widths typically range from 40.6 cm to 50.8 cm
g) Back Height from Seat Rail: Backrest heights can vary based on user needs, often measured from the seat to the top of the shoulders

5. Types of Wheelchairs

5.1. Manual Wheelchairs

Manual wheelchairs are among the most common types, propelled either by the user or an attendant. They are lightweight, cost-effective, and suitable for individuals with sufficient upper-body strength.

Types of Manual Wheelchairs:

- Standard Wheelchairs: Designed for general use, often constructed with steel or aluminum frames. These models are durable and suited for short-term or occasional use [37][38].

- Lightweight and Ultralight Wheelchairs: Made from materials like aluminum or titanium, these wheelchairs reduce physical effort and are ideal for active users who require mobility over long distances [39].

- Recliner Wheelchairs: Equipped with adjustable backrests, these wheelchairs provide comfort for users who cannot sit upright for extended periods. They are also beneficial for individuals requiring postural adjustments [40].

- Sports Wheelchairs: Built for agility and speed, these wheelchairs feature customized designs tailored for activities such as basketball, tennis, and racing. Their lightweight and durable frames allow for high performance [41].

5.2. Electric (Powered) Wheelchairs

Electric wheelchairs use motors and batteries for propulsion, offering independent mobility for users with limited physical strength. They are especially beneficial for navigating diverse environments with minimal physical effort.

- Standard Electric Wheelchairs: Operated using a joystick or similar controls, these wheelchairs are versatile for both indoor and outdoor use. They provide stability and comfort for long-term mobility [42][43].

- Standing Wheelchairs: Enable users to transition between sitting and standing positions. These models improve circulation, reduce pressure sores, and promote greater independence in social settings [44][45].

- All-Terrain Wheelchairs: Designed with larger wheels, enhanced suspension systems, and robust frames to navigate outdoor terrains like sand, grass, and gravel. These are ideal for adventurous users or those in rural areas [46][47].

5.3. Specialized Wheelchairs

Specialized wheelchairs are designed to meet specific medical needs or adapt to unique lifestyles, providing greater flexibility and comfort.

Types of Specialized Wheelchairs:

- Pediatric Wheelchairs: Constructed with smaller frames for children, these wheelchairs are highly adjustable to accommodate growth and specific support needs [48].

- Tilt-in-Space Wheelchairs: Allow users to tilt the entire seat frame to redistribute pressure, prevent sores, and improve comfort. These models are particularly beneficial for individuals with severe disabilities who require frequent posture changes [49].

- Transport Wheelchairs: Lightweight and foldable, transport wheelchairs are intended for short-term use and are operated by caregivers. They are commonly used in hospitals or during travel [50].

- Bariatric Wheelchairs: Designed for users with higher weight requirements, bariatric models feature reinforced frames and wider seats for durability and comfort [51].

Table .1. Comprehensive Overview of types of wheelchairs

Category	Type	Weight Range	Best-Suited Environment	Right People
Manual Wheelchairs	Standard Wheelchairs	15–20 kg [37]	Smooth indoor/outdoor surfaces	Temporary users, such as post-surgery patients [37].
	Lightweight Wheelchairs	8–15 kg [37][38]	Travel and daily mobility	Active users, such as individuals with paraplegia [37][38].
	Recliner Wheelchairs	20–25 kg [53]	Indoor environments requiring extended sitting	Users are unable to sit upright for long periods due to fatigue or orthostatic hypotension [53].
	Sports Wheelchairs	6–10 kg [54]	Sports courts, tracks	Athletes participate in sports like basketball, tennis, or racing [54].
Electric (Powered) Wheelchairs	Standard Electric Wheelchairs	45–80 kg [55]	Indoor and outdoor on smooth terrains	Users with chronic disabilities like muscular dystrophy or arthritis [55].
	Standing Wheelchairs	90–130 kg [39]	Indoor and urban environments	Individuals with spinal cord injuries or cerebral palsy

				requiring standing capabilities [39].
	All-Terrain Wheelchairs	70–120 kg [43]	Outdoor terrains	Outdoor enthusiasts navigating sand, grass, or gravel [43].
Specialized Wheelchairs	Pediatric Wheelchairs	8–15 kg [56]	Homes, schools, and controlled environments	Children with spina bifida or cerebral palsy needing adjustable support [56].
	Tilt-in-Space Wheelchairs	20–30 kg [57]	Indoor settings requiring extended sitting	Individuals with ALS or advanced multiple sclerosis needing pressure redistribution [57].
	Transport Wheelchairs	8–12 kg [58]	Airports, hospitals, and short-term mobility	Patients requiring caregiver assistance during travel or medical care [58].
	Bariatric Wheelchairs	25–50 kg [59]	Wide spaces indoors and stable outdoor areas	Individuals with obesity require reinforced frames and wider seats [59].

6. Control Methods

6.1. Joystick

The joystick remains a critical component in electric wheelchair design, acting as the primary interface for controlling movement. By translating hand movements into directional commands, it enables users to navigate with precision and ease. Traditional joystick systems rely on proportional control, where the degree of joystick displacement determines the speed and direction of the wheelchair. This simplicity makes them accessible for a wide range of users [34].

6.2. Voice-control

Voice-controlled wheelchairs have become a significant advancement in assistive technology, enabling users with severe mobility impairments to navigate using verbal commands. These systems typically include a microphone for capturing voice input, a speech recognition module for processing commands, and a microcontroller that translates the commands into specific actions for the wheelchair, Fig. 10. Commands like "forward," "stop," or "left" are interpreted by the system, allowing users to control the wheelchair effectively without requiring manual input [35] [36].

Safety is a key consideration in voice-controlled systems. Ultrasonic sensors are often integrated to detect obstacles, ensuring the wheelchair stops or adjusts its path to prevent collisions. Some systems incorporate additional monitoring features, such as pulse or temperature sensors, to track the user's health during operation [37] [38]. Modern voice-controlled wheelchairs also feature mobile application integration, allowing users to pair the system with their smartphones via Bluetooth. This provides additional functionalities like command customization, real-time tracking, and adjustments for personalized control [39]. However, challenges such as background noise interference, varying accents, and speech patterns can affect recognition accuracy. Advanced noise-cancellation algorithms and adaptable speech models are being implemented to overcome these issues [40].

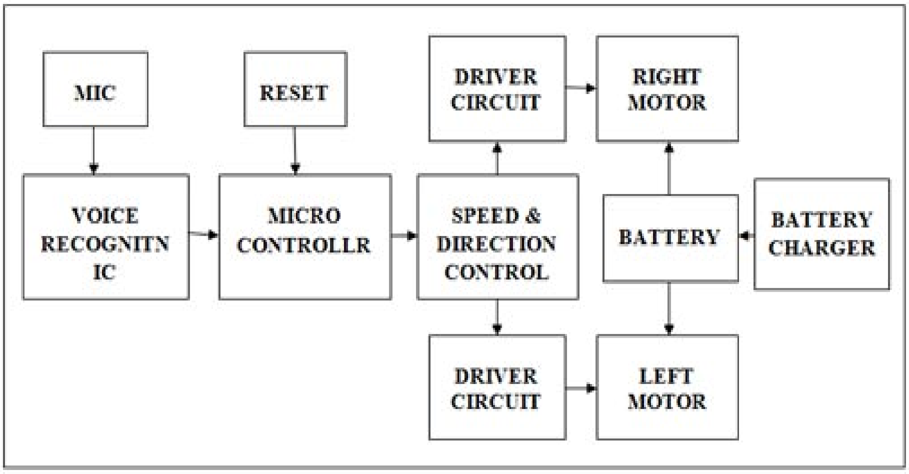

Fig. 10: Block Diagram of voice-controlled wheelchair for physically challenged people

6.3. Head movement control systems

Enable individuals with severe physical disabilities to operate wheelchairs using intuitive head gestures. These systems employ sensors such as gyroscopes, accelerometers, or vision-based technologies to detect head movements, which are then translated into navigational commands for the wheelchair. For instance, a system utilizing accelerometer sensors can detect head tilts to control wheelchair movement in various directions. When the user tilts their head forward, the wheelchair moves forward; tilting the head backward causes it to move backward; and tilting to the left or right directs the wheelchair accordingly. This method provides a hands-free operation, enhancing mobility for users with limited upper limb functionality [41] [42].

Safety features are integral to these systems. Incorporating obstacle detection mechanisms, such as ultrasonic sensors, helps prevent collisions by detecting obstacles in the wheelchair's path and stopping the movement when necessary [43] [44]. Additionally, patient monitoring systems, including temperature and pulse sensors, can be integrated to monitor the user's health status during operation. Advancements in vision-based technologies have led to the development of non-intrusive head movement control systems. These systems utilize cameras to capture head movements, eliminating the need for wearable sensors and enhancing user comfort. By analyzing head poses, the system can interpret user intentions and control the wheelchair accordingly, Fig11. Depiction of an electric wheelchair with an installed webcam for face detection and orientation estimation. Movement commands are generated based on the head's yaw and pitch, with clearly defined detection thresholds. This innovative solution provides intuitive control for individuals with limited mobility. [45] [46].

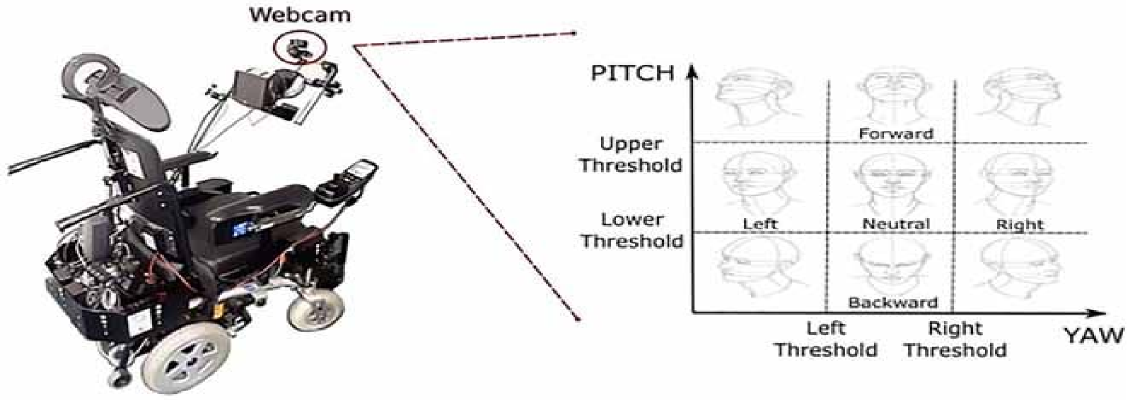

Fig.11. Electric wheelchair with an installed webcam for face detection and orientation estimation [5].

6.4. Sip-and-puff (SNP)

Sip-and-puff (SNP) systems are assistive technologies that allow individuals with severe physical disabilities to control powered wheelchairs using air pressure variations. Users inhale ("sip") or exhale ("puff") into a specialized mouthpiece connected to pressure sensors, which detect these inputs and translate them into specific directional commands. For instance, a hard puff can initiate forward movement, while a hard sip can move the wheelchair backward. Similarly, soft puffs and sips may turn the wheelchair right and left, respectively. This configuration provides users with a practical and accessible solution for independent mobility [47] [48].

The simplicity and affordability of SNP systems make them widely adopted, particularly for individuals with limited upper extremity function. However, these systems face challenges such as a limited command set due to their binary input nature, user fatigue from prolonged use, and environmental sensitivity to factors like temperature and humidity. Recent advancements include integrating SNP systems with autonomous navigation features to enhance safety and reduce the cognitive load on users. Comparative studies also highlight that while SNP systems provide essential mobility, alternative technologies, such as tongue-controlled systems, may offer improved accuracy and speed in certain scenarios [49] [50]. These developments continue to address existing limitations and expand the capabilities of SNP-controlled wheelchairs for diverse users [51].

6.5. Eye-tracking

Eye-tracking technology has revolutionized assistive devices by providing an alternative mobility solution for individuals with severe motor impairments. It allows wheelchair users to control movement through their gaze, offering independence and ease of navigation. Eye-tracking systems typically utilize cameras and infrared sensors to detect eye movements, translating them into directional commands for wheelchair operation. For example, a left gaze can initiate a left turn, while a prolonged blink might signal a stop, Fig.12, [52] [53]. Advanced algorithms and image processing techniques enhance accuracy and responsiveness, enabling real-time control [54].

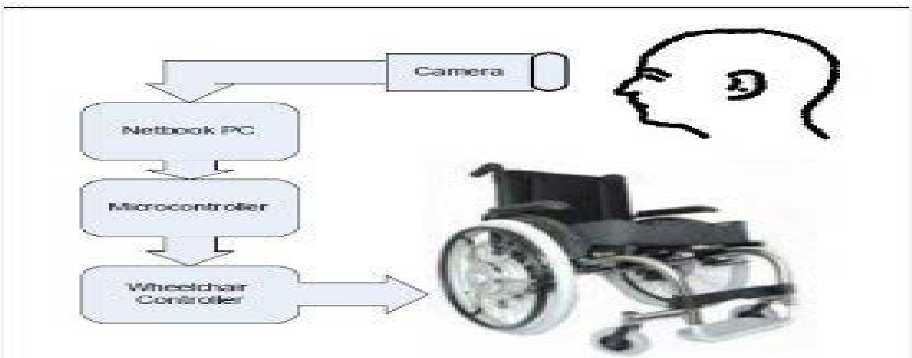

Fig. 12. Block diagram [52]

The integration of eye-tracking into wheelchair systems involves mapping eye movements to predefined navigation commands, processed through software that ensures immediate response to the user's input. Safety is a primary consideration, with many systems incorporating obstacle detection sensors to prevent collisions. Infrared sensors and real-time feedback mechanisms stop the wheelchair when obstacles are detected, ensuring safe operation in dynamic environments [55] [56]. Additionally, manual override options are included to allow caregivers to intervene when needed. User training and calibration are critical to the effective use of eye-tracking systems. Individual differences in gaze behavior require customized calibration to enhance accuracy and usability. The adaptability of these systems ensures that users can operate the wheelchair efficiently, even under varying lighting conditions or environmental factors [57]. Despite these advancements, challenges such as system latency, sensitivity to ambient lighting, and false detections remain. Future developments aim to integrate advanced machine learning algorithms, such as deep learning, to improve eye-tracking precision and enhance overall system reliability [54] [56].

6.6. Brain-Computer Interfaces (BCIs)

It is transformative technology that enables individuals with severe mobility impairments to control wheelchairs using neural signals. BCIs typically employ electroencephalography (EEG) to capture brain activity, which is then processed to decode user intentions into actionable commands for wheelchair navigation. A standard BCI system consists of several components: signal acquisition via EEG devices, signal processing to extract relevant patterns, command translation, and wheelchair actuation to execute movements [58] [59]. Popular control paradigms in BCI systems include motor imagery (MI), where users imagine specific movements, such as moving their hands to generate distinct EEG signals, which are then translated into directional commands [60]. Other methods involve Steady-State Visually Evoked Potentials (SSVEP), which rely on brain responses to visual stimuli flashing at different frequencies, and P300 evoked potentials, triggered by rare events like focusing on a flashing icon, Fig. 13, [61] [62].

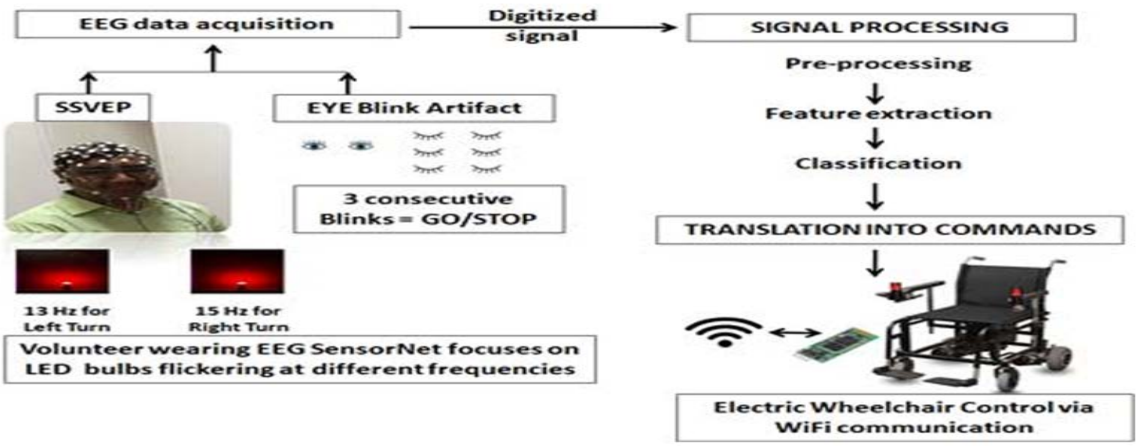

Fig. 13. Schematic diagram of the proposed SSVEP and eye blink based electric wheelchair control technology [60]

Hybrid BCI systems combine multiple paradigms, such as SSVEP with eye-blink detection, to enhance control accuracy and reduce response latency. These systems also incorporate safety features like obstacle detection using ultrasonic or infrared sensors, allowing autonomous navigation to prevent collisions while responding to user commands [63].

7. Conclusion

The evolution of wheelchair technology has been a testament to humanity's commitment to improving mobility and quality of life for individuals with disabilities. From early rudimentary designs to advanced smart wheelchairs equipped with artificial intelligence and assistive technologies, these innovations have transformed the way people with mobility impairments navigate their world. The integration of ergonomic design, adaptive controls, and multifunctional features such as reclining and standing capabilities underscores the progress made toward enhancing independence and comfort for users. Diseases such as spinal cord injuries, cerebral palsy, muscular dystrophy, and multiple sclerosis continue to necessitate the use of wheelchairs, making accessibility to these mobility aids a critical public health concern. However, barriers such as high costs, inadequate infrastructure, and societal stigma still hinder equitable access. Addressing these challenges requires a multifaceted approach, including the development of cost-effective designs, widespread implementation of inclusive policies, and integration of psychological and social support for individuals relying on wheelchairs. This review highlights the importance of continued innovation and collaboration among engineers, healthcare providers, policymakers, and advocacy groups to ensure that wheelchair technologies are accessible, adaptable, and responsive to the diverse needs of users. By prioritizing equity and inclusivity, future advancements in wheelchair design can foster greater independence, societal integration, and economic participation for individuals with disabilities, ultimately contributing to a more inclusive and equitable world

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