Balance and Gait Training in Stroke Survivors Using BCI: A Narrative Review

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ABSTRACT
Brain-Computer Interfaces (BCIs) have diverse applications in stroke rehabilitation, extending beyond cognitive functions to include environmental interaction, gait and balance improvement, communication, and cognitive rehabilitation. In the realm of gait and balance, BCIs contribute to enhanced neuroplasticity, neurofeedback training, and improved coordination. They are instrumental in aiding communication for stroke survivors with speech impairments and hold significant potential in cognitive rehabilitation through tailored interventions and neurofeedback. Task-oriented training with BCIs provides customized exercises, real-time feedback, and adaptive approaches for motor skills rehabilitation, fostering engagement and motivation. Integration with Functional Electrical Stimulation (FES) and Virtual Reality (VR) amplifies their impact, aiding in mobility, rehabilitation, and immersive therapy. Additionally, BCIs synergize with orthotics, exoskeletons, robotics, and intelligent wheelchairs, acting as a direct neural interface for enhanced control, mobility assistance, and personalized rehabilitation support. Ongoing research aims to refine BCI precision, improve user accessibility, and explore novel applications, emphasizing the transformative potential of BCIs in stroke rehabilitation across various domains. Brain-Computer Interfaces (BCIs) demonstrate promise in stroke rehabilitation by customizing neurorehabilitation exercises, aiding communication, supporting motor recovery, and assisting cognitive rehabilitation. However, challenges such as signal quality, long-term usability, and cost-effectiveness persist. Ethical concerns, privacy issues, and the need for robust validation through clinical trials are highlighted. Enhancing user-friendliness, addressing interface challenges, and tailoring interventions to individual needs are ongoing efforts. Overall, collaborative research and advancements are essential to unlocking the potential benefits of BCIs for diverse stroke survivors.

KEYWORDS: Stroke, Brain Computer Interface, Virtual reality, Functional electrical stimulation, Orthotics, Task specific Training

1. INTRODUCTION

STROKE

Stroke, also known as Cerebrovascular Accident (CVA) occurs when a part of the brain is deprived of blood supply. It leads to a sudden loss of neurological function. Various neurological deficits follow stroke, they are:

1. **Focal Deficits-** loss or decrease of consciousness or sensory, motor, cognitive, perceptual and language impairments.

2. **Motor Deficits-** Hemiplegia or paralysis and Hemiparesis or weakness. These occur on the side of the body opposite to the affected side.[2]

Rehabilitation is given to aid the patient's quality of life and help him/her to be independent. It also helps in reducing the known symptoms associated with stroke and minimize any disability. Rehabilitation requires a coordinated team of specialists to develop a Plan of Care (POC). The POC for rehabilitation considers the history of the patient, the symptoms developed, course and the activity restrictions along with impairments in the body. Types of POC: -

A. **Restorative-** it focuses on decreasing the impairments and activity limitations along with any restrictions.
B. **Preventive-** it helps in reducing any kind of complications and impairments.
C. **Compensatory-** it aims at altering the task, movement, and environment in order to make function better.[2]

Specific and goal-oriented reeducation strategies are important for a proper recovery. The strategies are based on a precise examination of the impairments and activity limitation present. Focus is on improving the motor control and strength of trunk and upper and lower limbs along with greater emphasis on the more involved side. the choice of strategy or intervention is based on- phase of recovery (acute, subacute, chronic), age, other accessory conditions, and financial and social status.[2]

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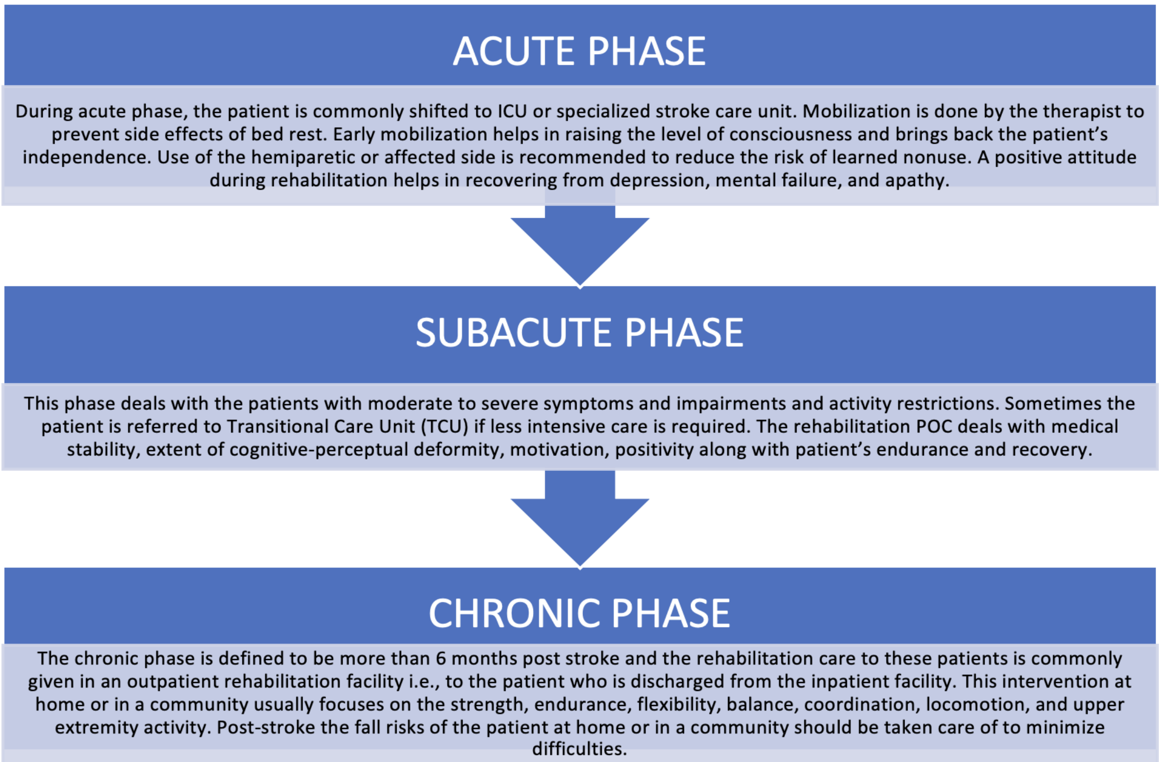

2. METHODOLOGY

The discussion about scope and usability of Brain Computer interface is ongoing. There have been much research around this topic but none of them have made to the final claims. Brain Computer Interface has been a topic of interest due to its usage in Health-related field. The role of Brain Computer interface in Rehabilitation is known but its variability and scope is yet to be sure about. This paper focuses on various aspects of the usage of Brain Computer Interface in Rehabilitation of Stroke Patients. Using PubMed, Scopus, Google Scholar, Science direct, We found out a total of 1136 articles around BCI aspects, mechanism, role in neurorehabilitation. In this paper we have used about 33 articles to narrow its various usage in Neurorehabilitation, especially Stroke.

BRAIN COMPUTER INTERFACE

The connection between the human mind and surroundings is possible due to the Brain-Computer Interface technology. This is because the brain-machine interface, or BCI, is a real-time tool and interacts with external factors outside the control of humans. For this reason, the BCI system interacts with the user by employing signals collected from the individual's brainwave activities that are transmitted to the computer which generates a response to the user.[3]

Through the Brain-Computer Interfaces, BCIs, an individual's intentions can be transmitted to external equipment like computers, voice synthesizers, assistive devices, and brain prosthetics. Since an interface like this can make such a difference in the quality of life and lower the costs of intensive care, it is a very viable option for people with extreme motor limitations.[3]

The idea of merging technology with human's brain has always been alluring, but with the rapid development of neurology and engineering, it is finally feasible. Such breakthroughs have opened up the opportunity to enhance human physical and mental abilities. The most significant medical applications have been deep brain stimulation for Parkinson's patients and a cochlear implant for deaf patients . In addition to medicine, brain-computer interfaces , also known as brain-machine interfaces have been utilized for telepresence, gaming, science, art, security, and human enhancement. Each application has a specific strategy with its own advantages and disadvantages.[4]

The future of BCI technology largely depends on the possibilities of improving performance and restricting day-to-day uncertainty. Most BCI systems have similar components, including signal acquisition, pre-processing, feature extraction, classification, and device control, despite their apparent diversity. The relationship between the brain and the computer is established in signal acquisition, and the data is gathered from brain signals . This signal is processed, and its features are extracted. The final object is device control, which is the end goal of using these signals in applications or prosthetics..[6]

BCIs use brain signals to understand what users want. First, they record brain activity and translate it into electrical signals. There are two main ways to monitor brain activity: electrophysiological and hemodynamic. Electrophysiological activity comes from chemicals that send messages between neurons. Neurons create electric currents that flow within and between groups of neurons. Hemodynamic response is when active neurons get more glucose from blood than inactive areas.[3]

Advances in brain signal analysis have helped people with severe disabilities use their brain signals for communicating and controlling things around them, working without their damaged muscles. Non-invasive EEG-based BCIs let users control computer cursors, robotic limbs, text processing, internet browsing, room controls, and entertainment. These technologies offer new independence to those with debilitating conditions like Amyotropic Lateral Sclerosis.[5]

BCI technology could also aid recovery from strokes or brain trauma by guiding brain changes. EEG brain signals show current brain activity, helping users reduce abnormal patterns. Alternatively, BCIs can supplement impaired muscle control, potentially enhancing rehabilitation protocols and improving muscle control for patients.[4]

Various types of BCIs include:

- Non-invasive BCIs: These BCIs do not require invasive procedures or direct brain penetration. Instead, they utilize external sensors to detect brain activity. Common non-invasive methods include electroencephalography (EEG), functional near-infrared spectroscopy (fNIRS), and magnetoencephalography (MEG).[4]
- Invasive BCIs: Invasive BCIs involve the insertion of electrodes or similar devices directly into brain tissue. This approach yields more precise and detailed brain activity measurements but comes with higher associated risks. In most cases, invasive BCIs are reserved for medical applications in severe conditions, such as restoring communication for individuals with complete paralysis.[4]

BRAIN COMPUTER INTERFACE IN STROKE

Brain-Computer Interface (BCI) technology is a valuable tool in stroke rehabilitation, offering innovative methods to aid and expedite the recovery process for individuals who have suffered a stroke. Stroke is a neurological condition that can lead to various physical and cognitive impairments, necessitating rehabilitation to help patients regain lost functions and enhance their overall quality of life.[6]

BCIs contribute to stroke rehabilitation in several ways:[6]

1. Motor Function Rehabilitation:

- BCIs enable stroke survivors with motor impairments to regain control over their affected limbs by translating their intentions or brain signals into commands that control external devices, such as robotic exoskeletons or computer interfaces.
- BCIs facilitate task-specific training, allowing stroke patients to practice movements that would otherwise be challenging due to physical limitations.

2. Neurofeedback and Brain Plasticity:

- BCIs provide real-time neurofeedback to stroke patients, helping them understand and enhance their brain's ability to rewire itself (neuroplasticity). This feedback can motivate patients and reinforce effective rehabilitation strategies.
- BCIs can guide and encourage stroke survivors to perform specific tasks, like hand and arm movements, based on their brain activity, thereby promoting neuroplastic changes.

3. Cognitive Rehabilitation:

- Stroke often leads to cognitive deficits, such as attention, memory, and executive function impairments. BCIs can be employed to design tailored training programs targeting these cognitive functions.
- BCIs can adjust the difficulty level of cognitive tasks based on the user's performance, making rehabilitation more personalized and engaging.

4. Speech and Communication Rehabilitation:

- Some stroke survivors face speech and communication challenges. BCIs can be utilized to create communication aids that interpret the user's brain signals and convert them into text or speech output.
- BCIs can assist individuals in regaining control over their vocal functions and facilitating speech therapy exercises.

5. Monitoring and Assessment:

- BCIs offer continuous monitoring of a patient's brain activity and rehabilitation progress, supplying valuable data to healthcare professionals. This data guides treatment adjustments and ensures that rehabilitation goals are met.

6. Home-Based Rehabilitation:

- If designed for home use, BCIs can allow stroke survivors to continue rehabilitation outside clinical settings, offering convenience and cost-effectiveness. This fosters long-term engagement and improved outcomes.

7. Assistive Devices:

- BCIs can be seamlessly integrated into assistive devices, such as wheelchairs and computer systems, making them accessible to individuals with severe motor impairments.

8. Research and Innovation:

- The application of BCIs in stroke rehabilitation generates substantial data for research into the brain's recovery capacity after a stroke, leading to advancements in our comprehension of post-stroke recovery.

BCI technology also holds great promise for addressing balance and gait impairments in stroke patients. Stroke often results in motor deficits, including difficulties with balance and gait, which can significantly impact mobility and independence.[5]

BCIs offer innovative solutions for balance and gait rehabilitation:

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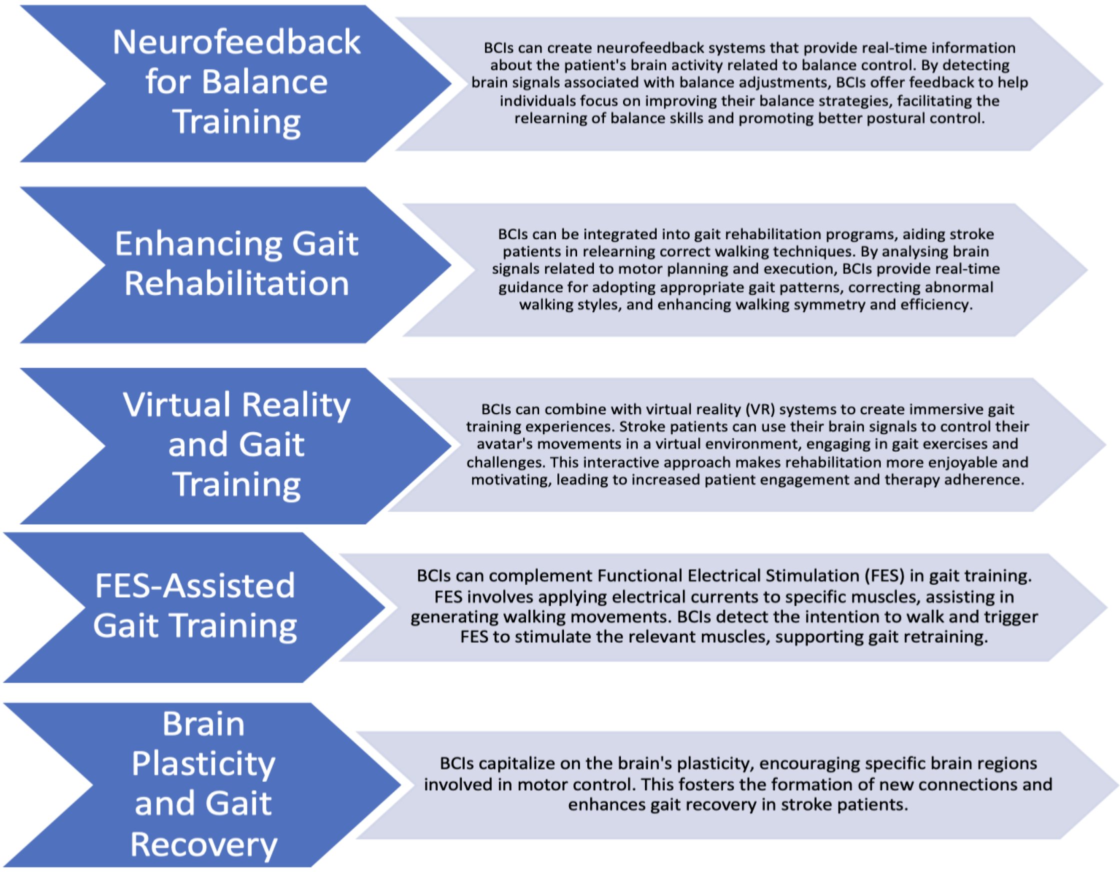

BCI MECHANISM

The creation and implementation of a Brain-Computer Interface (BCI) can differ depending on its specific use and the type of brain signals employed (e.g., EEG, fNIRS, or invasive signals). Nevertheless, the core algorithmic stages in a basic BCI system can be summarized as follows:[4]

1. **Signal Acquisition:** The initial phase of a BCI system involves gathering brain signals from the user. Typically, sensors or electrodes are used, placed on the scalp, or, in invasive BCIs, implanted directly into brain tissue. Common non-invasive brain signals include Electroencephalography (EEG), measuring electrical activity, and functional Near-Infrared Spectroscopy (fNIRS), tracking changes in blood oxygenation levels.
2. **Data Pre-processing:** The collected brain signals often contain noise and artifacts from various sources like muscle movements or external interference. Pre-processing methods are applied to clean and enhance the signals, eliminating noise and irrelevant information while preserving pertinent brain activity.
3. **Feature Extraction:** In this step, essential features are derived from the pre-processed brain signals to represent the user's mental states or intentions. These features should capture distinct patterns linked to various cognitive states, such as motor imagery, visual attention, or other mental tasks.
4. **Pattern Classification:** The feature vectors obtained in the previous stage serve as input for a classification algorithm. The classification algorithm's role is to deduce the user's intended action or mental state based on the extracted features. Common classification algorithms used in BCIs include support vector machines (SVM), linear discriminant analysis (LDA), and deep learning models like convolutional neural networks (CNNs) or current neural networks (RNNs).
5. **Calibration and Training:** Before employing the BCI for real-time applications, a calibration or training phase is typically conducted. During this phase, the user engages in specific tasks or mental activities multiple times to collect labelled training data. This data is used to train the classification algorithm and establish personalized mappings between brain activity patterns and user intentions.
6. **Real-Time Operation:** Following calibration and training, the BCI is ready for real-time use. The user's brain signals are continuously acquired, pre-processed, and fed into the trained classification algorithm. The algorithm interprets the user's mental states or intentions, enabling them to control a device or interact with a computer system.
7. **Feedback and Control:** BCIs often provide feedback to the user to enhance their control over the interface. For instance, if the user is controlling a cursor on a screen, they may receive visual feedback regarding the cursor's movement. This feedback loop aids users in learning and refining their control strategies.

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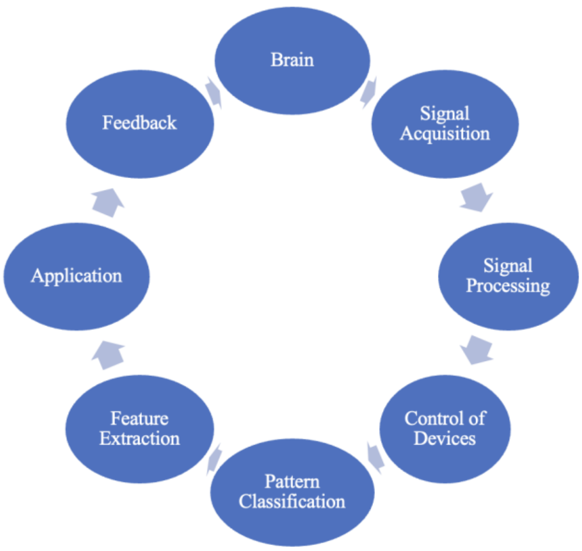

ROLE OF BCI IN IMPROVING GAIT AND BALANCE

According to research, BCI has been shown to help stroke victims with their balance and gait. Research indicates that FES training alone is not as beneficial for improving balance and gait function in stroke patients as BCI-based FES training is. The BCI-FES training outcomes indicate possible benefits for walking ability in patients with persistent hemiparetic stroke. BCI-FES's therapeutic efficacy in helping chronic hemiparetic stroke patients improve their postural balance and gait performance.[8]

- **Enhanced Neuroplasticity:** BCIs have the potential to facilitate neuroplasticity, which is the brain's innate capability to restructure itself by forming novel neural connections. When individuals recovering from strokes utilize BCIs to manage and enhance their stability and walking abilities, it can activate distinct neural pathways linked to these functions. Over time, this may result in enhancements in motor skills.[9]
- **Neurofeedback Training:** BCIs provide a platform for neurofeedback training, where patients receive immediate feedback on their brain activity. In the context of balance and gait, this feedback empowers patients to actively engage in refining their neural control over these functions, potentially leading to improved steadiness and walking patterns.[9]
- **Enhanced Coordination:** Stroke often disrupts the coordination among various muscle groups involved in maintaining balance and facilitating a smooth gait. When BCIs are integrated with rehabilitation devices such as exoskeletons or functional electrical stimulation (FES), they can assist patients in regaining better command over these muscle groups. BCIs can ensure that the timing and intensity of muscle activations align with the desired movements, thereby encouraging a more fluid and synchronized gait.[9]

BCI IN COMMUNICATION AND COGNITIVE REHABILITATION

Brain-computer interfaces link thoughts to devices. They translate a person's mind into commands for technology. These tools benefit stroke survivors facing speech or movement troubles. For those with those challenges, BCIs allow communication and control over surroundings.[23]

Research explores using BCIs for cognitive rehab after stroke. The interfaces may assist with training the mind, boosting memory, and improving focus. Tasks engaging certain brain areas via BCIs aim to aid cognitive recovery. They aim to restore functions affected when strokes impairs cognition.[23]

In summary, BCIs present a promising avenue for cognitive rehabilitation in stroke survivors, offering customized, adaptable interventions aimed at augmenting cognitive functions and aiding neural recovery.

TASK ORIENTED TRAINING WITH BCI

Brain-computer interfaces (BCIs) play an integral role in task-oriented training designed for stroke patients, presenting a cutting-edge approach to rehabilitative therapy. Below outlines their significant contributions:[31]

Customized Task Development:

BCIs enable the creation of tailored tasks specifically aligned with the unique requirements and capabilities of stroke patients. These tasks are finely adjusted to address the motor or cognitive functions affected by the stroke, resulting in a more individualized and efficient training program.

Motor Skills Rehabilitation:

In task-oriented training, BCIs support motor rehabilitation by facilitating exercises that foster motor learning and recovery. They enable stroke patients to engage in activities involving motor imagery or actual movements, providing instantaneous feedback and enhancing the process of relearning motor skills.

Real-Time Feedback and Monitoring:

BCIs deliver immediate feedback on brain activity, offering insights into a patient's participation and performance during task-oriented exercises. This feedback loop assists both patients and therapists in tracking progress, fine-tuning tasks, and adapting rehabilitation strategies as necessary.

Restoration of Functional Abilities:

Task-oriented training with BCIs focuses on reinstating functional abilities impacted by the stroke. Whether it involves regaining motor control, enhancing hand-eye coordination, or improving cognitive functions, BCIs aid in devising tasks that simulate real-life activities to promote functional recovery.

Adaptive Training Approach:

BCIs allow for adaptive training programs that adjust task difficulty levels based on a patient's progress. This adaptability ensures tasks remain suitably challenging, fostering continual improvement while preventing frustration during rehabilitation.

BCI WITH FES

Brain-Computer Interfaces (BCIs) work together with Functional Electrical Stimulation (FES). This helps people with neurological issues, spine injuries, or movement difficulties. The BCI lets the brain talk to devices like FES systems. FES uses electrical signals to make muscles move.[9]

Here's an overview of its functioning:[18]

1. **Neural Signal Acquisition:** The BCI component of the system captures neural signals emanating from the user's brain. This can be accomplished through various techniques such as electroencephalography (EEG), electrocorticography (ECoG), or the use of implanted electrodes.
2. **Signal Processing:** Subsequently, the neural signals undergo intricate processing and analysis via advanced algorithms to decipher the user's intentions or commands. These intentions may pertain to the control of specific movements or muscle groups.
3. **Command Generation:** Leveraging the decoded neural signals, the BCI formulates commands dispatched to the FES system. These commands specify which muscles to stimulate, as well as the intensity and timing of stimulation.
4. **Functional Electrical Stimulation (FES):** The FES system administers electrical stimulation to the targeted muscles, provoking them to contract and execute precise movements. For instance, if an individual with a spinal cord injury desires to move their arm, the BCI can transmit commands to the FES system, instructing it to stimulate the relevant arm muscles and enable arm elevation.
5. **Closed-Loop Feedback:** A pivotal facet of this system encompasses a closed-loop feedback mechanism. Sensors or feedback mechanisms can be integrated to furnish information regarding the condition of the user's muscles and limbs. This feedback can be employed to refine the control signals dispatched by the BCI, enhancing the precision and responsiveness of movements.

Applications of BCI-FES systems encompass:

- **Assistive Devices:** Individuals grappling with paralysis or motor impairments can harness this technology to govern prosthetic limbs, wheelchairs, or other assistive apparatuses.
- **Rehabilitation:** Its utility extends to physical therapy and rehabilitation programs, facilitating patients in regaining muscle strength and motor control following injuries or surgical procedures.[13]
- **Augmenting Independence:** BCI-FES systems have the potential to augment the independence and

overall quality of life for individuals confronting severe disabilities.[11]

While these BCI-FES setups seem very useful, they come with some difficulties too. They need to understand brain signals precisely. The electrical stimulation must be safe and reliable. There are also concerns about people using them long-term and getting used to them over time.[8]

BCI WITH VR

BCI and VR technology combinations are helpful for rehab. They're more fun than normal methods, keeping people motivated and shortening treatment time. These systems give helpful feedback to aid brain recovery. Stroke patients can use them often, showing their usefulness. But, the mix of BCI and VR is new, and data transfer rates need improving. There is much progress to be made before this technology can be effectively employed in the rehabilitation of patients with neurological conditions.[6]

Brain-computer interfaces (BCIs) show great potential when combined with virtual reality (VR) technologies, offering multifaceted support for stroke patients:[33]

Cognitive Rehabilitation:

Integrated BCIs and VR offer tailored cognitive exercises for stroke survivors. These exercises engage memory, attention, and executive functions, providing interactive tasks aimed at cognitive recovery.

Motor Rehabilitation:

BCIs in VR assist in motor rehabilitation by enabling stroke patients to engage in virtual tasks involving movements or gestures. By interpreting brain signals, these interfaces adapt VR scenarios to aid in motor relearning and improvement.

Immersive Therapy:

BCIs enhance the immersive nature of VR therapy for stroke patients. By interpreting brain activity, these interfaces can adjust VR environments in response to the patient's cognitive patterns, offering more personalized therapeutic experiences.

Functional Relearning:

Combined BCIs and VR environments serve as platforms for stroke survivors to relearn daily activities. Simulated VR scenarios allow practice in tasks like object manipulation or navigation, facilitating functional recovery.

Personalized Training:

BCIs integrated into VR enable personalized training programs. Monitoring neural signals helps adapt VR scenarios to the patient's abilities, adjusting difficulty levels or tasks for an optimized training regimen.

The integration of BCIs with VR presents an optimistic path for stroke rehabilitation, offering personalized and immersive therapies targeting cognitive and motor functions, potentially expediting the recovery process.

BCI with Orthotics, Exoskeletons, Robotics, and Intelligent Wheelchairs

Devices that support joints are very important for people recovering from strokes. These devices help with rehabilitation and improving movement. An orthotic device provides support to a joint when it needs to move from a still position to a moving one. It also helps the joint move through its full range of motion. This type of device is helpful for people with conditions like a disease that weakens muscles or severe muscle loss. Some researchers have made a system with two parts. It uses electrical stimulation and a special orthotic device. The goal is to help people with paralysis move their hands, fingers, and elbows again. Furthermore, consistent training with this system has the potential to reverse severe muscle atrophy

in paralyzed muscles, even years after the initial spinal cord injury.[6]
Brain-computer interfaces (BCIs) play a significant role in advancing the integration of orthotics, robotics, and exoskeleton technologies.[30]
Direct Control Interface: BCIs act as a direct communication channel between the brain and orthotic devices, robotics, or exoskeletons. By interpreting brain signals, users can control these assistive technologies, bypassing traditional manual controls. This direct neural interface enhances precision and responsiveness in operating these devices.
Enhancing Mobility: Integrated with orthotics, robotics, or exoskeletons, BCIs provide mobility assistance to individuals with mobility impairments. Interpreting brain signals enables more intuitive movement, facilitating walking, mobility, and task performance for those with limited mobility.
Rehabilitation Support: In rehabilitation settings, BCIs paired with orthotics, robotics, or exoskeletons aid in motor rehabilitation. By facilitating controlled movements, they assist individuals recovering from injuries or neurological conditions, supporting motor relearning and functional recovery.
Personalized Assistance: BCIs enable personalized assistance by interpreting individual brain signals to adjust device settings or movement patterns. This customization optimizes comfort and effectiveness, catering to the specific needs and capabilities of each user.
Real-time Adaptation: BCIs provide immediate feedback on brain activity, enabling instant device adjustments based on changing user needs or environmental conditions. This feedback loop enhances safety and usability.
User Accessibility: Focus is directed towards making BCIs more user-friendly and accessible. This involves simplifying interfaces, improving device comfort, and refining user training for effective control through brain signals.
In summary, BCIs act as a transformative link between the brain and assistive technologies like orthotics, robotics, and exoskeletons. They revolutionize mobility support, rehabilitation, and personalized assistance for individuals with diverse neurological conditions or mobility limitations.

DISCUSSION

Brain-computer interfaces (BCIs) prove helpful for stroke rehab. New approaches highlight BCIs' role in recovery and improving quality of life for stroke survivors. Recent studies show BCIs' evolving role in managing stroke. BCIs enable custom neurorehab exercises for stroke patients. For those with speech issues, BCIs can aid communication by decoding brain signals to select words or phrases on a computer screen. They also support motor recovery by leveraging brain plasticity. By linking brain signals to robotic exoskeletons or prosthetic limbs, patients can regain lost motor functions by controlling external devices through thoughts. They can assist with cognitive training tasks, like memory and attention exercises, while monitoring patient progress.[12]
Even so, using BCIs has challenges. Recent research notes issues like needing better signal quality, being able to use them long-term, and making them cost less.[9] Researchers work hard to make BCIs more user-friendly and practical for stroke patients. New studies show promising results, but long-term data is needed to confirm lasting therapy benefits.[6] While challenges remain, ongoing research and technology advances keep expanding possibilities for BCIs in stroke treatment.[16] Making BCIs simpler, more comfortable, and reliable is crucial for wider acceptance. But ethical frameworks must also evolve alongside technology. For BCIs to prove effective in stroke rehab, large clinical trials and real-world testing are necessary.[21] Enhancing user-friendliness and accessibility of BCIs stands as a critical factor for wider acceptance.

Addressing challenges related to interface simplicity, comfort, and reliability remains an ongoing endeavour. Validating the effectiveness of BCI research in stroke rehabilitation necessitates larger-scale clinical trials and real-world implementations. To prove BCIs really work and who can use them, we need strong studies with many different people..[21]

CONCLUSION

Brain-computer interfaces connect brains to computers. They let disabled people control devices with their minds. BCIs could aid stroke survivors in regaining functions like cognition, balance, and coordination. Researchers study combining BCIs with stimulators, virtual worlds, and robotic gear. This multimodal approach aids post-stroke rehabilitation. Still, cost, customization needs, and performance pose hurdles. Despite challenges, BCIs offer hope for comprehensive stroke recovery. Their potential inspires continued research and innovation. Affordable yet durable BCIs that meet individual requirements remain a coveted goal. Overall, BCIs' promise drives efforts to overcome barriers hindering widespread adoption in stroke rehabilitation. Ethical concerns, privacy issues, and the importance of informed consent must also be given due consideration.[11]

In short, BCIs show great hope in stroke recovery. They can help people talk better, aid the brain's healing, help arms and legs move, improve balance and walking, and teach us how the brain responds to strokes and rehab. More research in this area could greatly improve life for stroke survivors. [12]

ACKNOWLEDGEMENT

I, Vanshika Arora, would like to express my gratitude to Dr. Meena Gupta of Amity University, Department of Amity Institute of Health Allied Science for her unwavering support for my research and for spending a great deal of time reading my work numerous times. Her expertise and passion gave me proper direction. I would also like to thank my friends and family for much needed inspiration and help.

CONFLICT OF INTREST

There is no conflict of interest.

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