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Investigation of Brain Computer Interface Based Exoskeleton in Rehabilitation

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ABSTRACT

Background of the study: The integration of Brain-Computer Interface (BCI) technology with exoskeletons has introduced novel solutions in the field of neurorehabilitation. BCI-based exoskeletons harness neural signals to control robotic limbs, offering enhanced motor restoration, improved patient engagement, and potential autonomy for individuals with disabilities. BCI-based exoskeletons offer a modern approach by utilizing neural signals to control robotic devices, enhancing movement ability and promoting rehabilitation in patients with motor dysfunctions. This article discussed recent advancements in BCI technology in the context of exoskeletons and analyzed the integration of BCI with exoskeletons.

Methodology: A literature review was conducted using IEEE Xplore to identify original studies from 2018 to 2023 implementing BCI-exoskeleton systems for clinical populations. Inclusion criteria required studies to involve clinical populations using BCI-exoskeletons for either upper or lower limb rehabilitation. Descriptive analysis and linear regression were applied to evaluate input signal types (EEG vs. EMG) and rehabilitation outcomes.

Results: All selected studies involved stroke patients, predominantly using EEG signals. EEG-based systems showed 67% greater improvement rates compared to EMG systems, though the result was not statistically significant ($p = 0.200$). Key challenges identified included limited clinical trials, high cost, bulky design, system safety, and lack of pediatric applications.

Conclusion: BCI-integrated exoskeletons represent a promising advancement in rehabilitation, enabling personalized and neuroadaptive support for individuals with motor dysfunctions. However, clinical validation remains limited for outcomes in real-world settings.

Keywords: *Brain-Computer Interfaces, Exoskeleton Device, Electroencephalography, Neurological Rehabilitation, Stroke Rehabilitation, Motor Activity.*

INTRODUCTION

The area of rehabilitation engineering has witnessed major advancements during last few years, specifically with the emergence of brain-computer interface (BCI) technology. BCIs has bridged communication between the human brain and external devices, which has created new opportunities for assistive technologies. For example, BCI technology has been merged with

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motor imagery (MI) systems for promoting rehabilitation, while engaging the participants[1-3]. Another great application of BCI technology is in the development of exoskeletons for rehabilitation. Exoskeletons are wearable robotic structures designed to assist and augment the physical capability of those who have experienced mobility dysfunction. By merging BCIs in exoskeletons, it has led to possibility to utilize neural signals to control the movement of robotic limbs which can promote motor functional recovery in patients with neurological disorders such as stroke, spinal cord injury (SCI), or Cerebral Palsy (CP). This article aims to investigate the implementation of BCI-based exoskeletons in rehabilitation and highlight challenges and opportunities for future research and development.

METHODOLOGY

A search in IEEE Xplore was run to identify the emergence of BCI based exoskeletons in rehabilitation between 2018 to 2023. The syntax used for search was: *(BCI OR Brain Computer Interface) AND (Rehabilitation) AND (Disability OR Motor dysfunction) AND (Exoskeleton)*. The inclusion criteria of the studies was to have at least one participant from clinical population, implementing BCI based exoskeleton for rehabilitation of either Upper Limb (UL) or Lower Limb (LL). Review articles were not included. The search led to nineteen studies, after screening through inclusion criteria only five studies were selected. Details of the selected studies are summarized in Table-1.

Table-1 shows the studies based on BCI exoskeletons in rehabilitation

S/N	Ref.	Clin. Pop.	#	Input Signal	Rehab. task	Exo	Self-Design / Branded	FDA App.	Outcome
1	[2]	Stroke	4	EMG	UL	HrWE	Self-Design	No	NR
2	[3]	Stroke	4	EEG	UL	-	Self-Design	No	Improved
3	[4]	Stroke	2	EEG	LL	BCLLE	Self-Design	No	Improved
4	[5]	Stroke	10	EEG	UL	-	Self-Design	No	NR
5	[6]	Stroke	10	EMG	UL	-	Self-Design	No	NR

Most of the studies rejected, during screening process, were due to no participant from clinical population, however, some of the rejected articles were review articles. This indicates that most of the work done in the domain was outside the clinical setting. It can also be perceived that recruiting clinical population is more challenging, as compare to healthy population, specifically, those who have experienced lower limb weakness[4]. Except two studies[5,6] all other selected studies had less than ten participants, from clinical population. The small number of participants would not represent the participation of clinical population to the considerable extend. All the studies selected had a clinical population from Stroke. It can be inferred that most studies during last five years had majorly worked towards stroke rehabilitation.

Most studies[3-5] used Electroencephalography (EEG), as type of input signal for BCI systems, followed by Electromyography (EMG)[2,6], this highlights the significance and suitability of EEG to be used as an input for BCI-EXO systems, for real time operations. The linear regression was performed to analyze the relationship between input signal type (EEG vs. EMG) and rehabilitation results. Studies having EEG showed a 67% higher chances of improvement as compared to EMG, though this effect was not statistically significant ($p = 0.200$). Descriptive statistical analysis indicated that 66.7% of EEG studies reported improvement, while none of the EMG studies was identified, this suggests a potential trend favoring EEG- based interventions.

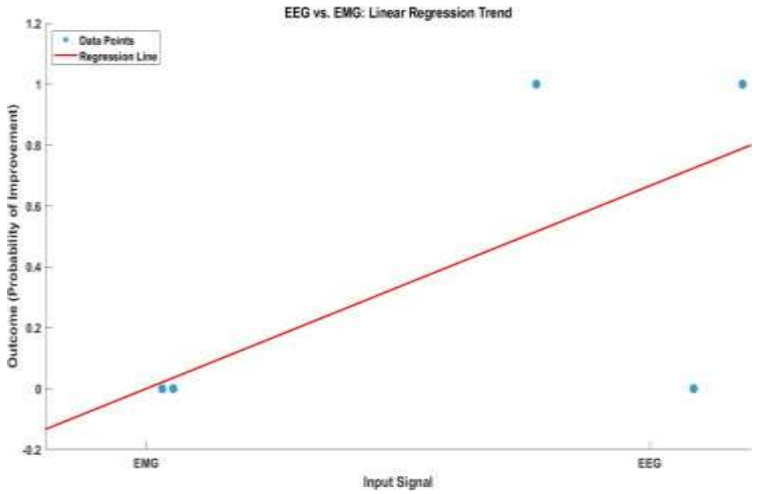

Figure-1 Linear Regression comparing EEG vs EMG as types of input for improving outcome

Almost all studies were aimed at upper-limb rehabilitation, some specifically targeted Hand, this finding highlights the preference of rehabilitation for those having upper limb weakness, this also indicates the complex nature of restoration of upper limb system. All exoskeletons identified were self designed by authors and none of them was FDA approved. It can be clearly inferred that the BCI-EXO systems are at their early stage of development. Interestingly, only two studies[3,4], reported improvement in clinical outcome, e.g., improved Range of motion (ROM), which identifies major gap in BCI based exoskeleton research during last five years.

Brain-Computer Interface Technology

Brain-computer interface (BCI) refers to a direct communication pathway formed between the brain and an external device, decoding neural signals into motor commands, as defined by Wolpaw and Wolpaw[7]. The history of Brain-computer interface can be traced back to the discovery of electrical activity within the Brain by Hans Berger[8]. That was first time ever when concept of EEG was introduced and the term brain wave was coined, referring to the variation of amplitude and frequency of electrical waves of Brain. Berger also suggested the usage of these electrical activities of Brain for diagnosis purpose, such as, epilepsy and other clinical conditions related to Brain[8]. The term Brain-computer interface (BCI) was introduced by Jacques Vidal in 1973[9]. It was first time ever, when the concept of controlling the machines directly through Brain signals were discussed. Vidal also discussed signal processing techniques for interfacing, he talked about EEG signals, feature extraction and classification of these signals and real time implementation of it[9]. He also discussed challenges and future direction of BCI, where he talked about improving signal to noise ration and enhancing BCI systems, in real time[9].

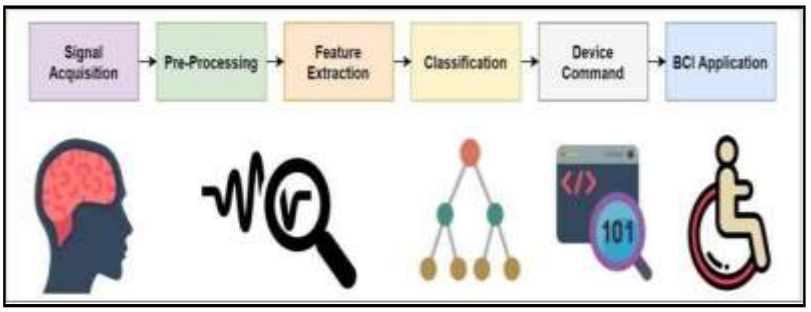

Figure-2 Basic design and operation of any BCI system[10]

There are different areas where BCI has been implemented for improving and augmenting the experience of people working in different domains. BCI has been implemented for emotion recognition and observing different moods, which can be utilized for promoting digital markets, and enhancing Human-robot interaction[11]. BCI has been revolutionizing the gaming industry, including serious games which are

being used for rehabilitation purposes. It allows player to enter and control in virtual environment and interact with different contents of the environment through their brain signals[12]. In avionics, BCI is being used by pilots for controlling aircrafts. By using purposefully designed EEG headset, unmanned aerial vehicles (UAVs) are being controlled through BCI systems[13]. However, the greatest and most purposeful implementation of BCI systems have been identified in rehabilitation. There are several ways through which these systems are being incorporated for rehabilitation purposes. Firstly, they can be used for controlling assistive devices, for example prosthetic limbs, wheelchairs and exoskeletons can be controlled through BCI[14]. With BCI, neurofeedback system can be implemented, which can enhance restoration process by facilitating motor learning of people experiencing different motor impairments, including Stroke and Spinal Cord Injury (SCI)[15]. Thirdly, BCI is helpful for regulating independent control of end user. Through assist as needed feature, which can be implemented through BCI, patient can regulate their brain states. They can choose switching between active and resting state, which makes them feel more confident and motivated towards their participation for functional restoration[16].BCI technology has the potential to revive rehabilitation by empowering direct communication between the brain and external devices. With BCI, individuals having neurological disorders can control robotic exoskeletons, promoting motor function recovery and enhancing independence. This technology includes the type of neural data used for communication, signal acquisition techniques e.g., EEG, signal processing method, and BCI operation paradigms (e.g., motor imagery, event-related potentials). BCI systems are very effective when it comes to patient engagement through real time feedback. The neural feedback from interfaced virtual and physical devices helps in real time adjustments of the system, as per patients need[17]. Successful implementation of BCI systems can lead to better performance than conventional robotic systems[3].

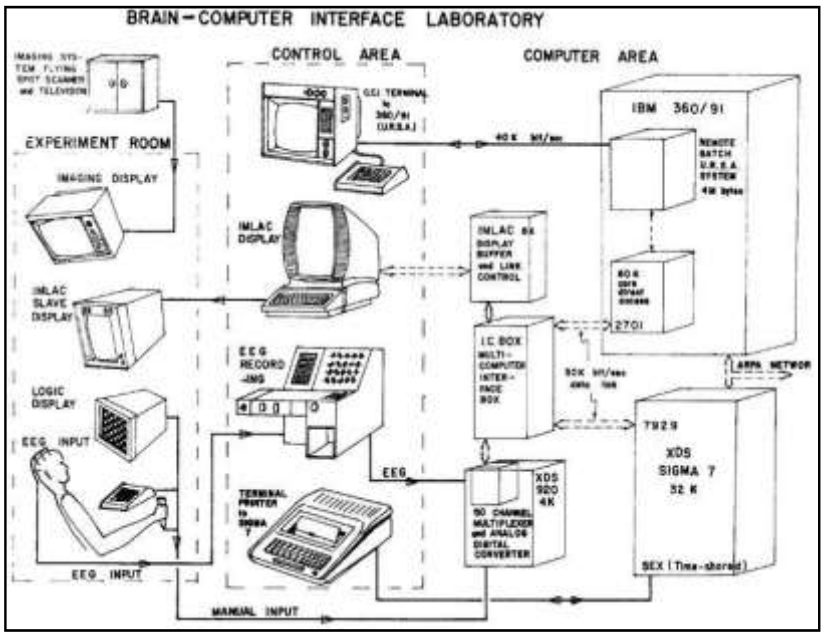

Figure-3 Computer architecture of the BCI Lab in UCLA in 1973[9]

Exoskeletons in Rehabilitation

Exoskeletons are wearable robotic systems designed to enhanced or restore physical function, often implemented in rehabilitation to help individuals with mobility impairments[18]. Exoskeletons can be traced back in history during 1890's, where exoskeleton like structure was designed and implemented for movement assistance. It was designed by an engineer from Russia, named Nicholas Yagn. The machine was passive in nature and used compressed gas in bags to help the movement[19].

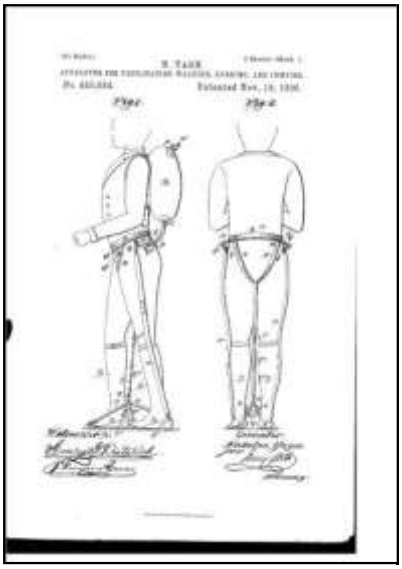

Figure-4 The first Exoskeleton design by Nicholas Yagn[19]

The first Exoskeleton designed for medical purpose is considered to be *Cyberlegs*, designed by Dr. Jean Callewaert during 1985. The design was for population experienced Spinal Cord Injury (SCI). The testing revealed its capacity of standing, walking and even climbing stairs[20]. Wearable robotics, especially exoskeletons, offer modern solutions to improve human performance and support rehabilitation interventions[21]. Exoskeletons have some great features which make them suitable for modern solutions for restoring motor function of PWDs. For example, Exoskeletons promote user-based approach, that not only makes it assistive technology but also therapeutic, which motivates user for rewarding recovery[3]. The exoskeletons implemented for rehabilitations are either specifically designed to support upper limb or lower limb, there are very limited exoskeleton which were designed to support whole body. The difference between nature and complexity of tasks between upper and lower limb is one of the major reasons for design specification.

Figure-5 Exoskeleton helps PWDs to be more independent[22]

Integration of BCI with Exoskeletons

BCI systems can be integrated with different types of physical and virtual devices, including but not limited to Virtual Reality (VR) devices, Functional Electrical Stimulation (FES) systems, and Exoskeletons. However, integration of BCI systems with exoskeletons offer greater advantages. The advantages of combining BCI and exoskeletons, includes improved precision, customization, and enhanced patient involvement, are highlighted. Different case studies and experimental findings have shown the suitability and effectiveness of BCI-based exoskeletons. BCI is usually connected with exoskeletons through Artificial Intelligence (AI) or Machine Learning (ML) algorithms[1]. The higher the robustness of algorithm will lead to better classification of signal, which will eventually lead to higher efficiency of systems performance, LDA is an example of one of the most frequently implemented algorithms for BCI- EXO systems[1]. One of the important examples of exoskeletons in rehabilitation is its utilization for upper limb rehabilitation in stroke patients[23], which is emerging and has a potential to completely revolutionized future of stroke rehabilitation, as already identified in literature review for last five years.

Figure-6 Typical BCI controlled Exoskeleton setup

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DISCUSSION

The BCI-based exoskeletons have a revolutionary potential for providing modern solutions to contemporary challenges associated with rehabilitation process of people experiencing different types of motor impairments. However, there are also certain challenges proposed by that. Benefits include accelerated motor recovery, improved patient motivation, reduced recovery time and personalized rehabilitation protocols. Challenges include highly personalized rehabilitation protocols including very specialized training to individual user, environmental noise which has a potential to interfere signal to the device, very high cost of system, bulky structure of exoskeleton, time consuming setup and system reliability. One of the major challenges that contemporary BCI-EXO systems have is Safety. The Food and Drug Administration (FDA), USA has classified exoskeletons as Class- II medical device, i.e., the exoskeletons that are approved by FDA lies under the category of moderate to high risk and should only be used in the presence of trained personnel[24]. One of the major reasons for EXO based therapies being categorized as class II medical devices is there challenging nature of being independently used by the end user, as they require extensive physical and mental efforts to control the EXO, which can lead to tiredness to patient and eventually put under the risk of losing control[25].

Moreover, BCI- EXO also possesses threats from its environment and is still under the developing stage for being used independently. As per Centers for Disease Control and Prevention (CDC),

adults aged sixty-five years and older, especially if they are experiencing any medical conditions leading to motor dysfunction, are under a great threat of falling. This fall has caused around 36000 deaths in the year 2020, making it leading cause for injury-based death and causes around $50 billion per year[26]. However, there are some studies working towards the identification of fall, associated with people wearing exoskeleton. A work done by Akshay et al.[27,28] is one of its examples. They collected EEG, EMG and Kinematic data, associated with balance loss of a person while wearing exoskeleton. The work compared the conditions in similar environment, when participants were wearing the exoskeleton and when they did not. They reported no differences in two different data sets, which explains no mechanical constraint being identified when a person experience balance loss while wearing EXO and while not wearing it. Also, they reported early detection of balance loss (around 75-134ms after the onset of external balance loss signal) through EEG signals (64 channel EEG system), same signal was preceded to muscles identified through EMG, after around 75ms delay (approx. 180ms after the onset of perturbation). The change on kinematic signal, i.e. Change in Centre of Pressure (COP) was observed around 350ms, after the onset of perturbation. This means the upcoming BCI-EXO systems will be more robust. Future BCI-EXO devices shall be able to deal with environmental threats, such as surviving a hit in real environment, that people usually experience in their daily life. Hower, most of the work is being done on healthy participants, due to their easy availability and less experimental and financial requirements, set through experimental protocols[28]. Another major gap identified related to BCI-EXO systems is they are specifically designed for adults. Except few studies[25,29], There is hardly any work known that is exclusively being performed for BCI-EXO based rehabilitation of children suffering with motor dysfunction, like Cerebral Palsy (CP).

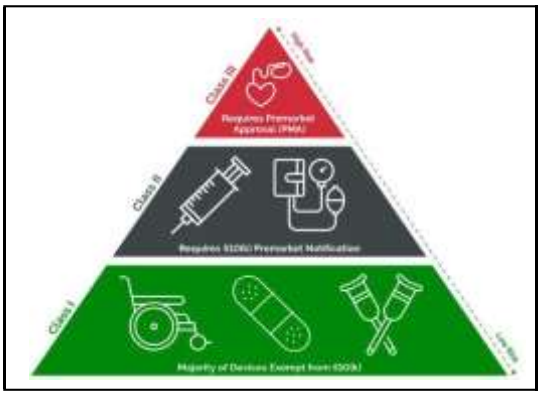

Figure-7 Class distribution of Medical Devices by FDA[30]

Conclusion

In conclusion, BCI-based exoskeletons hold significant promise as advanced tool for rehabilitation, offering a more practical approach to restoring motor function and improving quality of life for individuals with neurological disorders and motor impairments. However, challenges remain, continued research and development efforts are most likely to bring extensive advancements in this exciting field. Future investigation includes topics like optimization of BCI algorithms which may provide robust operation of BCI- EXO systems, development of user-friendly interfaces which can be handled independently by end user, integration with improved virtual and augmented reality environments for improving engagement of end user, and long-term clinical trials from multiple clinical populations, to assess higher efficacy and usability.

AUTHORS' CONTRIBUTION:
The following authors have made substantial contributions to the manuscript as under:
Conception or Design: Mansoor Mughal, Tariq Javed
Acquisition, Analysis or Interpretation of Data: Muhammad Faris, Tariq Javed
Manuscript Writing & Approval: Mansoor Mughal, Muhammad Faris, Tariq Javed

All authors acknowledge their accountability for all facets of the research, ensuring that any concerns regarding the accuracy or integrity of the work are duly investigated and resolved.

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