A review on brain computer interfaces: contemporary achievements and future goals towards movement restoration.

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ABSTRACT: Restoration of motor functions of patients with loss of mobility constitutes a yet unsolved medical problem, but also one of the most prominent research areas of neurosciences. Among suggested solutions, Brain Computer Interfaces have received much attention. BCI systems use electric, magnetic or metabolic brain signals to allow for control of external devices, such as wheelchairs, computers or neuroprosthetics, by disabled patients. Clinical applications includespinal cord injury, cerebrovascular accident rehabilitation, Amyotrophic Lateral Sclerosis patients. Various BCI systems are under research, facilitated by numerous measurement techniques including EEG, fMRI, MEG, nIRS and ECoG, each with its own advantages and disadvantages.

Current research effort focuses on brain signal identification and extraction. Virtual Reality environments are also deployed for patient training. Wheelchair or robotic arm control has showed up as the first step towards actual mobility restoration. The next era of BCI research is envisaged to lie along the transmission of brain signals to systems that will control and restore movement of disabled patients via mechanical appendixes or directly to the muscle system by neurosurgical means.

Key Words: Brain computer interface, Disability, Mobility restoration, Neuroprosthetic.

INTRODUCTION

Severe motor impairment and disability can be caused by many clinical situations and constitutes a challenge yet unmet by contemporary medicine[1]. Ranging from appendix movement loss to high spinal cord damage and from upstarting Amyotrophic Lateral Sclerosis (ALS) to complete locked-in syndrome, these situations mostly remain effectively uncured. Patients in those cases share one common characteristic: a severed link between thought and action, meaning a block between the transmission of the patient's will to move, speak or otherwise communicate with her surroundings (thought) and the actual movement, speech and communication (action). Bridging those two elements has been a focal point of many research fields, including pharmacology, biology and genetics and, lately, neuroinformatics. The concept of Man-Machine Interfaces (MMI) has been under research essentially since the 80s[2] (and perceived soon after by science fiction), but only in the 90s and onwards has solidified itself into the formed, separate scientific field of Human-Computer Interaction (HCI) and, more specifically and importantly, the field of Brain-Computer Interfaces (BCI)[3]. Those interfaces aim to somehow "restore" the loss of brain-environment communication and bypass the cause of that loss, thereby posing as a promising solution/treatment to the aforementioned medical conditions.

Brain Computer Interfaces are systems that use brain activity to interpret voluntary movement thought to control of external devices such as, computer cursors and computers, wheelchairs and neuroprosthetics and robotic arms[4]. Brain activity is identified by electric, magnetic or metabolic brain signals as extracted by depictive methods already used in medicine and is classified, analysed and translated by computer software to be appended to device control functions. Among those methods, electroencephalography (EEG)

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has been more extensively applied probably because it is a quite accurate and direct technique of inferring neural activity, it is inexpensive, widely available and relatively simple as a method[5]. A variety of other methods have been used in experimental protocols, each exhibiting relative advantages and disadvantages, and have provided an elaborate picture of brain activity during factual or imaginary motor functions. Among the newest and most promising methods, functional Magnetic Resonance Imaging (fMRI) and near-Infrared Spectroscopy (nIRS), in particular, address effectively two important parameters towards designing a functional BCI - as the former holds the gold standard in spatial accuracy of activity depiction[6] but the latter shares similar characteristics with the EEG (particularly mobility, availability and cost)[7]. As the goal of BCI research is actual human mobility restoration, every BCI system has to meet a set of characteristics to be effective, namely system mobility, real-time function, accuracy and artefact rejection. Nevertheless the current phase of BCI research is (rationally) occupied with accuracy and artefact rejection and many papers that measure and compare different methods, techniques and protocol accuracies, deal with classification of imaginary movement and signal processing[1]. Disabled patient rehabilitation may still be a remote objective but in the past five years a number of reports detail experiments involving wheelchair[8] or robotic arm control[9] through BCI methods, thereby consisting a major breakthrough towards addressing clinical situations effectively[3].

The aim of this paper is to review advances in the aforementioned BCI research as these apply to specific clinical conditions like the Locked-in syndrome, ALS, spinal cord injury (SCI), chronic stroke and others. Emphasis is placed on efforts towards movement restoration through current technological solutions for those conditions. Research problems and gaps are identified in an attempt to shed light into possible future research explorations. So, the remaining of this paper is structured as follows. In the next section, various clinical conditions are supposed and current BCI application efforts are described. Technology innovations regarding external device control are provided in section 3 and discussed in the last section of the paper.

MAJOR BCI-APPLICABLE CLINICAL CONDITIONS

2.1 *Locked-in syndrome*

The locked-in syndrome is a dramatic state that describes patients who, while being awake and retaining consciousness, they are incapable of producing limb and facial movements and unable to communicate verbally[10]. Patients retain vertical eye movement which can be used for non-verbal communication but even that is severely limited in the acute phase (obstructing possible evaluation of cognitive functions) because of shifting alertness and inconsistency or exhaustion of eye movement[10]. As a result, those patients can be falsely declared as comatose (medical doctors' unfamiliarity with the syndrome unfortunately play a very "crucial role" here) and wrong decisions regarding the patient's life support may be made, although ten year survival rates with proper support and care have been reported up to 80%[10]. Should the patient survive the acute phase and positively identified as entered a "locked-in syndrome", the main problem arising is that of establishing a proper form of communication. The recording of P300 Event Related Potentials (ERPs) in patients with locked-in syndrome[11] and other findings that indicate cognitive function steered research in a direction showing that cerebral metabolism and EEG signals are only mildly affected[12] and can possibly be exploited for the operation of a BCI system. However, the cause and depth of the syndrome represent important factors regarding the success of such a system. While external device utilization appears to have significant results in the case of brainstem lesion induced locked-in syndrome, this is not true for cases where the locked-in syndrome is ALS-induced (and especially when it is complete)[3]. Certain papers indicate that complete locked-in ALS patients could not learn any BCI function, in spite of retaining unimpaired cognitive functionality (as asserted by ERPs)[1316]. This is associated to a "thought extinction process" by certain reviews[3].

2.2 *Amyotrophic Lateral Sclerosis (ALS)*

ALS is a progressive neurodegenerative disorder, of uncertain cause, that primarily involves the motor neurons of cortex, brainstem, and spinal cord (upper and lower motor neurons)[17]. An impressive variety of factors are known to have an effect on the disorder's pathogeny, namely the mutations of superoxide dismutase (SOD1) (an enzyme that catalyses the disputation of superoxide radical anions to hydrogen peroxides and oxygen molecules), autoimmunological factors and many others (like neurotoxins, glutamate toxicity and neurodiseases, etc). The disorder causes a set of symptoms ranging from peripheral muscle atrophy and limb spasticity to oropharyngeal dysfunction and respiratory failure, although it seems to retain sphincter function and ocular movement up to the latest stages[18]. This disorder is age-related and ultimately fatal, and at the later stages patients need often mechanical life sustenance and, since nearly all bulbal muscles are affected, up to the point of complete paralysis, they suffer from loss of communication and interaction with the environment[17]. This need for communication was addressed by a number of clinical studies using non-invasive EEG-based BCI systems that proved that even in the latter stages of ALS, a certain quality of life could be maintained[19].

P300-BCI systems, in particular, have demonstrated certain advantages (especially less necessity for lengthy training and faster presentation rates of trials[3]) over other non-invasive approaches. Successful examples of this appear in two pieces of research where suitable applications of P300-BCI in four dimensional cursor control are demonstrated[20,21] thereby offering the promise of successful arm motor function restoration. However, the similar research has also showed that in latter stages of ALS, P300-BCI becomes ineffective, as it relies extensively on normal attention span and the ocular modality, which are harmed in those stages as the disease insults the ocular movement and muscles - a problem that could be addressed by usage of auditory input (a method that in its own account is less accurate and more difficult to learn[22]). An excellent editorial[3] summarized the progress of this path of research up to 2006 with a title that pinpointed the need for the BCI research to become more mature in ways of clinical applications. More recent work has produced even better results in terms of accuracy[23], classification and higher bit-rate[24], but overall, it can be presumed, that the special characteristics of this disease (especially the atrophy of the frontal lobe which seems to pace with the impairmentof cognitive functions and inability of proper usage of BCI systems) render ALS patients less probable to be fully benefit from BCI technology soon. Researchers seem to agree to the fact that significantly more ALS patient-involving research is crucial towards this goal.

2.3 *Spinal Cord injury (SCI)*

Acute trauma to the spinal cord is a common cause of paralysis ranging from paraplegia to complete tetraplegia according to the level of the injury. High spinal injury can be the cause of complete paralysis, rendering the patient unable to move any but facial muscles[25]. The interval from the injury to spinal cord death ranges significantly (from 20 minutes to 9 months) and for a partial injury to progress to complete necrosis, both primary and secondary injury mechanisms play important roles[25]. While the attempt of spinal cord preservation and restoration is a field for biological, pathophysiological and pharmacotherapeutical studies, an important issue that concerns BCI research is restoring motor functions and mobility to already installed and irreversible paralysis and regaining a certain level of quality in patients' life[26]. Unfortunately, although studies involving primates (rhesus monkeys and rats[27]) demonstrated significant results, human spinal cord injury studies have met not easily explainable difficulties[1]. Although paralysed patients cannot move muscles below the respective level of the injury, studies involving fMRI have demonstrated that during an attempt to move (an imaginary movement) their sensorimotor cortices activate almost normally[28] or possibly only at a weaker level compared to healthy subjects[29]. Until recently, as reported by certain extensively reviewed studies, experiments using sensorimotor rhythm BCI (SMR-BCI)[30] or multielectrode implants in the hand region of motor cortex[31], produced poor results, not applicable to everyday life[4]. This is bound to change in the near future and more clinical studies are once again a necessity to study the performance gap between primates and humans (or between healthy subjects and tetraplegic patients) and the actual application of movement restoration BCI systems to patients with spinal injury. To that direction, an EEG based BCI study[32] produced promising results in terms of accuracy, simplicity and training time shortening, but also stumbled upon the same explanatory gap, protruding the need for more clinical studies.

2.4 *Chronic stroke (cerebrovascular accident)*

Chronic stroke represents a clinical problem with severe effects on the patient, family, community and society as it remains the capital reason for long-term adult disability. Lasting disability is the common effect of this condition (among others, like speech impairment, loss of memory and reasoning ability, coma or death) occurring to almost two thirds of surviving patients (deaths from chronic stroke have been reduced to less than one third of cases thanks to immediate treatment procedures), with hand paralysis present in almost half of those patients. BCI based rehabilitation for this clinical condition has not received a lot of attention yet and only a few studies have addressed the issue, though with significant results. Among these, recent SMR/MEG based (magnetic encephalography)[33] and EEG based[34] BCI studies have succeeded in demonstrating the usefulness of BCI applications in chronic stroke patients. Results ranged from proving that BCI-naive hemiparetic patients can, in fact, successfully use Motor-Imagery based BCI (MI-BCI) and that their accuracy is not affected by the extent of motor impairment[34], to actual usage of a flexible artificial limb attached to the paralysed arm through training of SMR regulation[33]. More clinical studies involving chronic stroke affected patients are once again the key for a successful application of BCI technology to this condition. In that direction, a recent study[35] used ECoG (electrocorticography) and proposed a different possible methodology, taking advantage of certain findings (electrophysiological features related to ipsilateral movement) that can be used for external device usage. Another study involving healthy subjects[36] used event related de/synchronisation (ERD/ERS) methodology on EEG signals to predict movement occurrence, having a possible value in chronic stroke, among other BCI applicable conditions.

2.5 *Other applications*

Epileptic seizure control and attention regulation in the attention deficit-hyperactivity disorder (ADHD) are two of the most important BCI applications. Both lie as untypical applications of this technology (and beyond the scope of movement restoration), but have produced some very interesting (at least) results. Several studies using slow cortical potential (SCP) and SMR BCIs, starting from animal epilepsy regulation[37] and progressively moving to humans[38-40] demonstrated that through training patients to voluntarily regulate brain activity in certain areas, they would control epileptic seizures and remain seizure-free for long periods -even in drug-resistant epilepsy- and even show some increase in cognitive abilities and IQ. Similarly in ADHD, regulation of brain activity could produce results comparable to medication treatment (by methylphenidate)[41,42], this being credited to an increase in general of the ability for attention adjustment.

External device control and technology innovations

3.1 *Wheelchair control and application of Virtual Reality environments*

The most probable BCI technology to widely provide mobility restoration to disabled patients (before actual reanimation) is wheelchair control. Its advantages lie mainly within the simplicity of movement pattern and the (by fact) implementation of an appropriate platform for a mobile BCI system to be mounted on the wheelchair. In the very least, a BCI-controlled wheelchair could provide patients with certain autonomy within the confines of an appropriate accommodation and, through development, even beyond that. BCI research has turned its attention towards wheelchair control and a number of papers deal with this perspective. Supplementary to this approach (but not exclusively) the application of Virtual Reality environments (VR) in training have provided a controllable field for research experimentation. Through VR, researchers study the potentials and limitations of imaginary movement and easily all manipulate necessary parameters of (virtual) movement control. Of course brain-activity controlled virtual environments is a technology not confined to BCI training, as it is mostly awaited by the computers game industry for commercial use and other associated exploitations (such as military for instance).

Although both applications of BCI technology are relatively new, there are already a number of studies that have produced significant results. A P300-BCI system using 8 arrows for direction selection for wheelchair steering announced 95% accuracy and 7 commands/min rate[43]and offered adaptive performance. Another asynchronous EEG based BCI study[44] assessed the feasibility and consistency of wheelchair mental control, using both a real and a simulated wheelchair and shared control between the BCI system and the intelligent simulated wheelchair. It reported impressive results in accuracy in two experiments (assessing system consistency over time and different contexts and assessing performance in complex and random paths) with the only drawback being the low number of subjects. This particular approach of complex robotics is expected to be tested on disabled patients for assessment. Prior to the aforementioned papers, a great deal of effort was expended in VR studies that produced promising results. 3Class BCI systems were used for virtual directional control[45] and virtual robot control[46] with good results in accuracy. Moreover, another asynchronous (self-paced) study demonstrated for the first time wheelchair control in VR by a tetraplegic subject[47]. In a virtual setup of a street filled with avatars, the subject successfully navigated from avatar to avatar with a performance of 90% - 100% in single runs. Thus the latter experiment validated this technology's usefulness for disabled patients, thereby establishing the urgent need for more studies involving disabled patients from different causes. Self-paced BCIs present a more natural interface between human and machine by offering online training and adaptability, but they pose greater challenges than cue-paced (synchronous) BCIs, because the user's intention and timing is usually not known. Cue paced BCIs on the other hand offer known triggers and ignore off-time signals, but lack the adaptability of self-paced. The majority of BCIs currently are synchronous, and both methods are being under research for wheelchair control, without conclusive results over one or another's superiority.

The usage of Virtual Reality environments has offered a lot in terms of defining goals for BCI research. A novel paper involving imaginary feet movements for virtual robot control[48], characteristically named "walking from thought", is such an example. It demonstrated that imaginary feet movement can be used for navigating through VR environments in a series of experiments. It can, therefore, be said that a goal is set based on this - the actual reanimation of disabled patients using imaginary movement and a means to interpret them into real movement (such as an exoskeleton or neurosurgical interfacing the computer and the muscle system of the patients). In another recent study, an EEG-BCI based on a probabilistic neural network, presented hand grasping and holding sequences in a VR environment[49]. The experiment obtained classification accuracy from 85 to 93% showing that even more elaborate movement sequences can be reproduced by brain-computer interfaces. Even more, Virtual Reality environment training has been claimed to improve performance and feedback control (especially for BCI-naive subjects) when compared to conventional methods of feedback[50], such as simple visual presentations.

3.2 *Robotic arms and neuroprosthetics*

As BCI research progresses, so does arise the need for more accurately classifying intricate and elaborate movements, such as the movements of the hand. This derives from the possibility of restoring such movements to patients with limb loss or limb function loss (such as those from tetraplegia or chronic stroke). Neural prosthetics are devices used to link the central nervous system with machines. While those systems constitute a whole different field of neuroscience and neural engineering, there are cases where neuroprosthetics and BCI applications overlap, most important examples of this being the invasive BCI systems that use cortical implants to record motor brain signals and relate them to specific movements.

Movement reproduction, after limb movement-related signal extraction, is currently applied to a robotic arm[8] or a virtual arm or artificial flexible device attached to the paralysed arm[49] (this being the closer approach to hand reanimation at this moment). A number of studies researching restoration of upper limb movement, as in other areas of BCI research, have produced valuable results. Accurate classification of intention to generate shoulder versus elbow movement (two joints whose relative area in motor cortex lie in close proximity) by a time-frequency synthesized spatial patterns (TFSP) EEG BCI[51] is actually an effective example of this, reaching an average recognition level of 89% in four healthy subjects. More importantly in the same study a hemiparetic subject (after chronic stroke) achieved a recognition level of 76%. Another demonstration of a non-invasive method was achieved by real time fMRI (rtfMRI) two-dimensional control of a robotic arm[8], a method that uses blood oxygenation level dependant (BOLD) signals, which originate from the corresponding motor areas. Though performance level of subject was inferior to that achieved in other studies, this paper reported relative but undeniable success.

Be it invasive or non-invasive methods alone, this area of research has one feature in common with the rest of BCI research areas, which is the lack of clinical trials with disabled subjects. In those studies where patients were involved[51], their performance was inferior to that of healthy subjects, but that cannot even nearly be credibly assessed. This need for clinical studies involving patients is also asserted by data that show changes in somatotopy (representation of body areas in the motor cortex) following long-term spinal injury or amputation[52]. It is possible that reorganisation of the motor cortex can actually occur in such conditions, more extensively in long-term injury. Another recent study that[53] emulated mouse control (multidimensional movement and selection) using EEG BCI, involved two wheelchair-confined patients (SCI) - both achieved high performances, but the level of spinal damage was not affecting upper limb control.

3.4 *Different approaches of Brain-computer interfaces*

EEG based brain computer interfaces are the most common and more extensively researched. Significant knowledge of brain activity during actual or imaginary movement has been derived by multiple experiments using variants of EEG BCI systems. Nevertheless, such systems appear to have limitations - though by no means it can be said that EEG BCIs have reached their limits – in terms of classification accuracy, spatial resolution and performance, though it is probable that through research such limitations will be overcome. Among other approaches of brain computer interfaces, fMRI based ones allow very region-specific signal extraction and it is expected that through MRI usage expansion and real time analysis tools emergence, this technology will become more available[8]. fMRI uses brain oxygenation level dependant (BOLD) signals, an indirect method of measuring metabolic activity that corresponds to neuronal activation, that can be used mostly in self-regulation based BCIs[8]. fMRI BCI systems have been studied in robotic arm control[8] and its application in stroke rehabilitation[54] is under research. Studies demonstrated that modification of motor cortex functionality can occur as a response to fMRI feedback[55] a process that resembles changes in somatotopy after spinal injury or stroke. Research is being conducted towards the facilitation of such reorganisation in order to be used by fMRI BCI systems for movement restoration.

Near-Infrared Spectroscopy (nIRS) based BCI systems are another innovative approach of this technology. The method itself is not new, as it is being used for haemodynamic studies of the brain for more than thirty years now[56], but its potential in brain computer interfaces has not been researched until recently. NIRS BCI paradigms have been now proposed for decoding subjective preferences with 80% accuracy[57] and other studies demonstrated the feasibility of nIRS usage for brain activity recognition and its potential for BCI use, taking into account the method's low cost, safety and high accuracy[7]. Complete nIRS brain computer interfaces are currently under development[58] and are expected to prove significantly advantageous in the near future among other state-of-the-art BCI methods, such as magnetic encephalography (MEG) based systems. MEG BCI systems are a different approach, although based on the same physics principles that generate EEG, that have produced comparable results to the most advanced applications of EEG and ECoG BCIs[59] and are also expected to be more thoroughly studied in the near future.

DISCUSSION

It can be said that Brain-computer interface technology is passing through puberty and rapidly approaching adulthood. BCI research has recently passed that critical point that separates a promising idea from an applicable and useful technology, but it seems to still retain a level of immaturity. Since the conception of the possibility of movement restoration through BCI systems, and the first studies of the mid-90s, a lot of research has been conducted and a lot more is yet to come. Brain computer interface technology is bound to fulfil its role in movement restoration as soon as all studies converge to the same resolution; then its clinical application is just one step (or so) from realization.

It is not possible to decide upon a specific BCI method to be universally applied on all possible situations. Each method proves its own advantages (and fights to solve its problems), but some guidelines to be followed may include certain characteristics. System mobility and simplicity are among them, if BCI systems are to be used in everyday life, and that could possibly exclude methods like fMRI. On the other hand, no research can be labelled as useless, since e.g. fMRI can provide us with valuable knowledge on brain activation, maybe more than any other technique. Different EEG based BCIs seam more mature in terms of clinical application, while other rising methods (such as nIRS) yet await to be tested more extensively. On the whole, BCI research has to shift towards the conduction of significantly more clinical studies that involve patients, rather than healthy subjects, and proceed towards addressing all difficulties and inconveniences met in each different patient group. Up to this day, only a small number of studies have included patients but this has got to change, if one were to design brain computer interfaces useful in everyday life.

In summary, the future goals of BCI research can be arbitrarily divided in two groups, namely, short-term and long-term. The first group includes a set of goals that their realization could take less than five years, among them lies the aforementioned urgent need for more patient-involving studies. The development of widely available methodologies for brain signal extraction and tools for processing could provide the scientific community with some useful paradigms, and facilitate interconnection between research groups and their results. Several research groups have already made their tools and appropriate documentation available online for assessment, so as to enable more laboratories to engage in relevant research. As for actual mobility restoration, the development of wheelchair control technology could probably be the main short term goal and perhaps the first application of BCI that will reach -along with other types of BCI applications, like P300 spelling devices- wide scale clinical and commercial use. The second group, of long-term goals, has not been completely defined yet, as further development of BCI technologies towards specific directions has to be based upon the clinical findings and the degree of success of short-term goals. Firstly, accurate classification of very elaborate, complex and multi-muscular movements (imaginary and real) should be the objective of studies to come[60], as movement restoration of disabled patients has to evolve, in some point, to actual reanimation. This term, in particular, implies the usage of the patients' own functional muscular system. That would be the target of processed brain signals, through the implementation of neuroprosthetics and neurosurgical methods that will bypass the severance of thought/action coherence.

List of abbreviations:

ADHD	*Attention deficit - hyperactivity disorder*
ALS	*Amyotrophic Lateral Sclerosis*
BCI	*Brain Computer Interface*
BOLD	*Blood oxygenation level dependent*
ECoG	*Electrocorticography*
EEG	*Electroencephalography*
ERD	*Event related desynchronization*
ERS	*Event related synchronization*
ERP	*Event related potential*
fMRI	*Functional Magnetic Resonance Imaging*
HCI	*Human-computer interaction*
MEG	*Magnetic encephalography*
MI	*Motor imagery*
MMI	*Man-machine interface*
nIRS	*Near-infrared spectroscopy*
SCP	*Slow cortical potential*
SCI	*Spinal cord injury*
SMR	*Sensorimotor rhythm*
TFSP	*Time frequency synthesized patterns*
VR	*Virtual Reality*

Ανασκόπηση στις διεπαφές εγκεφάλου-υπολογιστή: σύγχρονα επιτεύγματα και μελλοντικοί στόχοι στο δρόμο για την αποκατάσταση της κίνησης ασθενών.

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ΠΕΡΙΛΗΨΗ: Η αποκατάσταση κινητικών λειτουργιών των ασθενών με έκπτωση της κινητικότητας αποτελεί ακόμη ένα άλυτο ιατρικό πρόβλημα, αλλά και ένα από τα πιο προέχοντα ερευνητικά πεδία των νευροεπιστημών. Ανάμεσα στις προτεινόμενες λύσεις, το πεδίο των Διεπαφών Εγκεφάλου-Υπολογιστή (BCI) συγκεντρώνει αρκετή προσοχή. Τα συστήματα BCI χρησιμοποιούν τα ηλεκτρικά, μαγνητικά ή μεταβολικά εγκεφαλικά σήματα για τον έλεγχο εξωτερικών συσκευών όπως αναπηρικών αμαξιδίων ή υπολογιστών από ασθενείς που έχουν απωλέσει την κινητικότητα τους.Οι κλινικές ενδείξεις περιλαμβάνουν την κάκωση του νωτιαίου μυελού, την αποκατάσταση αγγειακών εγκεφαλικών επισοδείων, την πλαγιομυατροφική σκλήρυνση (ALS). Διαφορετικά συστήματα βρίσκονται υπό έρευνα (συμπεριλαμβάνοντας μεθόδους όπως EEG, fMRI, MEG, nIRS, ECoG).

Οι σύγχρονες έρευνες εστιάζουν στην αναγνώριση και καταγραφή των εγκεφαλικών. Περιβάλλοντα Εικονικής Πραγματικότητας (VR) χρησιμοποιούνται επίσης για την εκπαίδευση των ασθενών. Ο έλεγχος αναπηρικού αμαξιδίου ή ρομποτικού χεριού αποτελεί το πρώτο βήμα προς την πραγματική αποκατάσταση κινητικότητας. Η επόμενη φάση της έρευνας πάνω στο BCI αναμένεται να αφορά την μετάδοση των εγκεφαλικών σημάτων σε συστήματα που θα αποκαθιστούν την κινητικότητα αυτών των ασθενών μέσω μηχανικών άκρων ή νευροχειρουργικών μεθόδων.

Λέξεις Κλειδιά: Αναπηρία, Αποκατάσταση κινητικότητας, Διεπαφή εγκεφάλου-υπολογιστή, Νευροπροσθετική.

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