Berkeley Pharma Tech
Journal of Medicine

Cognitive and Mobility Enhancement through Brain-Machine Interfaces and Neuroengineering

By: Roshni Nandwani, Srilakshmi Palanikumar, Sahaj Sidhu Singh and Jehan Balading

Correspondence:
roshni.nandwani@emory.edu

Keywords:
Brain-Machine Interface
Neuroengineering
Paralysis
Communication Disabilities
EEG

Submitted July 07, 2024
Accepted July 08, 2024
Published December 27, 2024

Full Open Access

Abstract

Brain-machine connections and neuroengineering are technologies that can be used to act as a direct communication pathway between the brain's electrical activity and an external device. This paper explores the realm of Brain-Machine Interfaces (BMIs) and neuroengineering technologies, focusing on their potential to address cognitive and mobility impairments. This comprehensive literature review delves into the current state of BMI technology, emphasizing its applications in stroke rehabilitation, paralysis management, prosthetics, memory enhancement, and communication solutions for speech impairments. Various methodologies, from invasive to non-invasive techniques, are examined for their impact on patients' quality of life. While these advancements hold great promise, they also pose ethical and practical challenges, including the need for further clinical testing, algorithm refinement, and affordability concerns. The future of BMIs is envisioned considering the role of artificial intelligence in expanding their possibilities and reflecting on the ethical considerations in deploying these technologies. This review provides valuable insights into the current landscape of BMIs, their potential for enhancing human capabilities, and the critical issues that must be addressed as the field progresses.

1. Introduction

The brain is often considered one of the most important organs in the human body because of the wide range of functions it performs. It is also extremely complicated, with over 100 billion neurons.[1] Equal numbers of neuronal and nonneuronal cells make the human brain an isometrically scaled-up primate brain.[2] As a result, managing diseases and impairments of the brain presents significant challenges. Modern science has begun to move away from looking at individual neurons, as it did in the past. Now, scientists are pivoting towards observing neural networks and neural ensembles. BMIs emerged from this direction of research.

A BMI is a computer-based system that acquires brain signals, analyzes them, and translates them into commands that are related to output devices. These commands then carry out desired actions, aiding the user to do things they previously would not have been able to.[4]

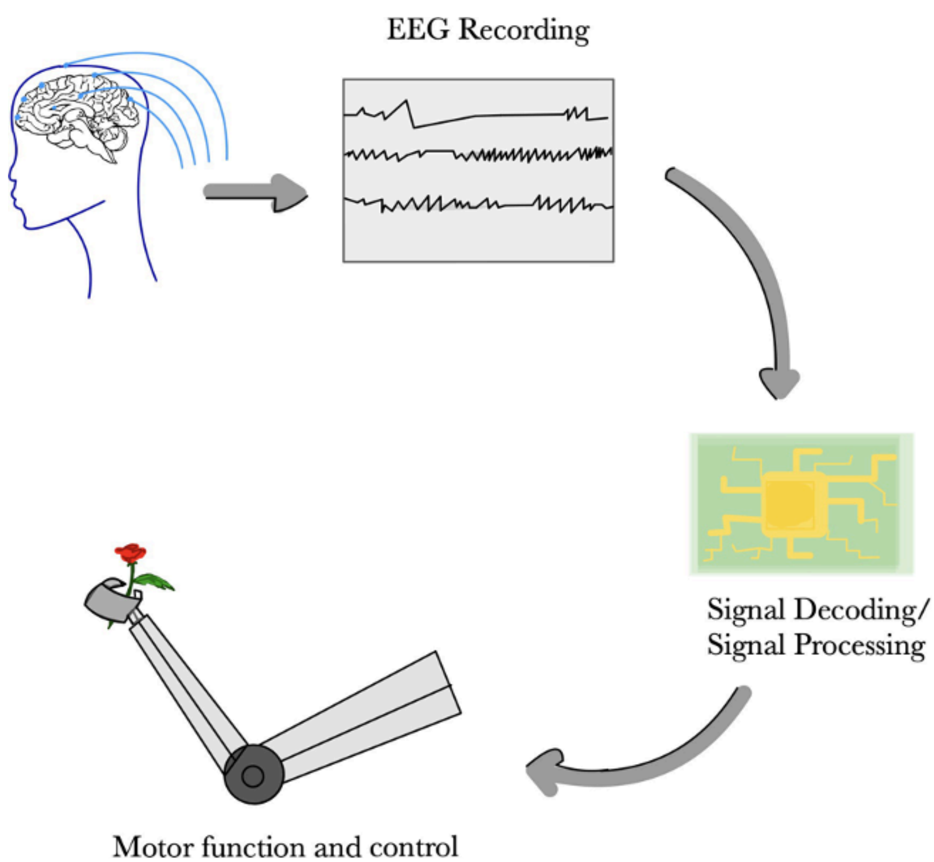

Figure 1. A Decoding Process Using an Invasive Method of EEG Recording to Yield Motor Function. The EEG recording decodes the brain's intentions, resulting in motor control of prosthetics and other external devices.

Research on brain-machine interfaces and brain-computer interfaces began as early as the 1970s. Tests were initially conducted on primate subjects until they were considered safe enough to be tested on humans in the 1990s.[5] As this technology evolved, ethical concerns increased in importance. Like with other kinds of medical procedures, finding a balance between repeated procedures on a highly sensitive organ and being able to have the BMI be as effective as possible poses various ethical concerns. Additionally, because BMIs are often used in treating cognitive afflictions, it is important to consider the patient's agency and consent.[6] Furthermore, the concerns related to data privacy and the potential for misuse of neural data upon conducting continuous monitoring of brain activity further raises questions regarding BMI technology ethics. The high amount of interest from the scientific community comes from the potential for BMIs to aid the rehabilitation of devastating diseases that are difficult to manage. In the past, they have shown capability in in regard to helping patients who are afflicted by strokes, chronic pain, paralysis, and other cognition and mobility-related problems.[7]

While current BMIs already offer significant amounts of aid in helping patients manage neurological disease, there are many open avenues for research in this field. For instance, artificial intelligence could bring various new possibilities to the applications of BMIs. Additionally, predictive models are believed to be able to bring function back to amputees and more severe cases of paralysis.[8]

In this review, though, we focus on the BMI and neuroengineering technologies that currently exist and have the potential to resolve various cognitive and mobility impairments. We review current scientific literature to gauge the potential of this technology in enhancing quality of life through BMI in memory, mobility, and home improvement technologies. We also look into potential areas of future research including the use of artificial intelligence with BMIs. Finally, we discuss the role that clinical trials have played in the current research in human subjects and their success/areas of improvement going forward.

1.2 Methods

In this review, we conducted a literature search of the sources, key studies, and findings describing issues and conditions related to BMI and cognitive and mobility impairments. Our literature review focused on the current technologies that exist to resolve and enhance the quality of life of those with mobile and cognitive impairments. Studies included in Table 1 met the criteria of being a recent study, published within the last 10 years, as well as fitting the keywords of BMI, neuroengineering, EEG, and the name of the condition or improvement technology. Our sources were collected from globally acknowledged databases, such as PubMed and ResearchGate. Prominent journals include the American Physiological Society, Science, Frontiers Neural Interface, and Journal of Neuroengineering. The information provided in the selected recent studies (ie. purpose of study, results of scientific findings, and impact of paper's outcome) were carefully evaluated and discussed in the following section.

2. Literature Review

2.1 Mobility Conditions

2.11 Stroke

Stroke is a sudden interruption of blood supply to the brain, causing damage to brain tissue. There are two primary types of strokes: ischemic and hemorrhagic, and both can be highly dangerous.[9] They often lead to motor deficits, communication impairments, and cognitive challenges.[10] Current stroke rehabilitation approaches include physical therapy, speech therapy, and pharmaceutical interventions. However, due to the complexity of stroke recovery, innovative methods like BMI are being explored as potential game-changers in rehabilitation.[11]

BMIs designed for stroke recovery work by decoding neural signals from the brain and translating them into meaningful actions.[12] This technology's application in stroke rehabilitation is a beacon of hope, particularly for those who have limited mobility or communication abilities. By allowing individuals to interact with the external world and control assistive devices directly with their thoughts, BMIs offer a new frontier for enhancing independence and recovery post-stroke.

There are two types of BMI based approaches to stroke rehabilitation: invasive and noninvasive. A popular technique associated with both of these approaches is signal acquisition. Invasive techniques use intracranial microelectrode arrays, while noninvasive techniques use electroencephalograms (EEG).[13] Both of these methods collect brain signals, which are then processed and decoded. A long-standing issue at this point is noise in signal decoding. They have been tested in clinical settings, and the findings are promising; they solidify the presence of BMIs as a method of rehabilitation for mobility conditions.

For example, a study exists that shows that BMI-based rehabilitation shows long-term improvements in the motor function of people with severe hand paresis. They found that BMI-based therapy, specifically targeting movements via EEG-triggered robotic assistance, led to lasting improvements in motor function six months after the intervention.[14] Similarly, another study was conducted in which 28 patients with motor deficits were treated with motor imagery (MI) training, and only half of them received BMI-based rehabilitation in addition. Fugl–Meyer Assessments showed that BMI-assisted rehabilitation was significantly more effective than pure MI treatments.[15]

Despite their potential, BMIs for stroke recovery face several challenges that must be addressed to fully recognize their benefits. One significant challenge is the need for more extensive clinical testing to validate the efficacy and safety of BMI interventions across diverse patient populations. Though initial studies have already indicated that BMI-assisted rehabilitation compared to motor imagery training alone have led to better outcomes, these findings need to be replicated in a larger, more diverse setting in order to ensure generalizability and further reliability.

Another critical issue is the fine-tuning of algorithms used in BMIs. The accuracy of such fine-tuning systems is dependent on their ability to decode neural signals precisely. Advances in machine learning and signal processing are imperative to create more robust and adaptive algorithms that can learn from patient data and improve performance over time.

Moreover, affordability is a major concern, as the high cost of developing BMI technology limits its widespread adoption. There are significant costs associated with intracranial surgeries and proper training and equipment, limiting accessibility to a broader patient population.

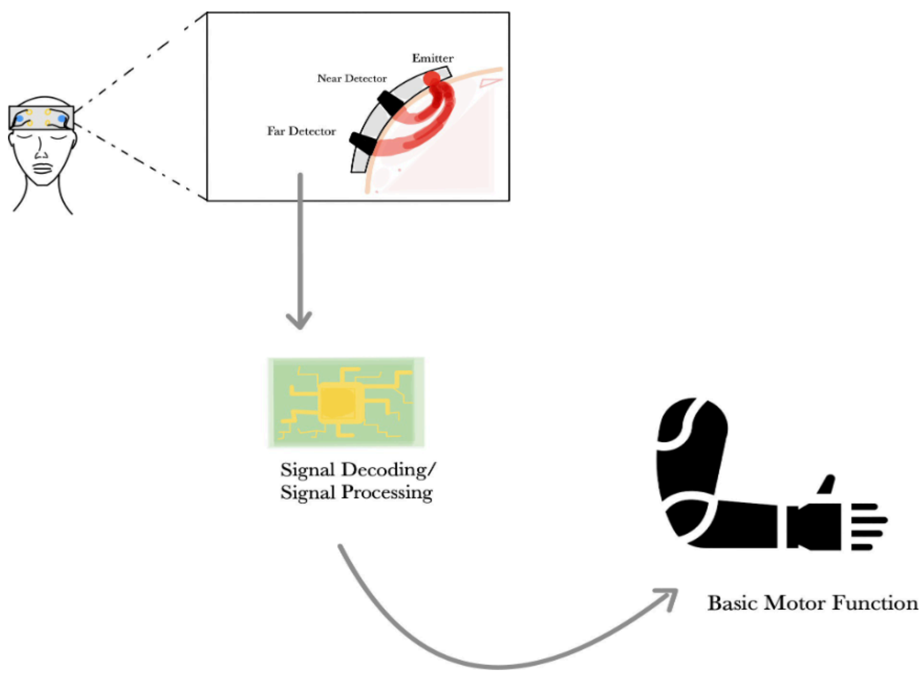

Figure 2. Functional Near-Infrared Spectroscopy (fNIRS) in Action. fNIRS is placed on the patient's head. The detector collects the data from the light emitter and then the data is transported and decoded (a computer). This data is used to control basic motor functions in a prosthetic.

2.12 Paralysis

BMIs have revealed potential in aiding individuals with paralysis resulting from amyotrophic lateral sclerosis (ALS), a disease that leads to complete loss of motor function and speech. In particular, BMIs have been instrumental in helping individuals communicate when they are in a completely locked-in state (CLIS). There are various types of BMIs, including EEG-based BMIs for ALS patients with functioning vision and eye control, and fNIRS-based BMIs (functional near-infrared spectroscopy) that offer spatial and temporal resolution, making them suitable for bedside applications. While EEG-based BMIs have achieved success in ALS patients with some motor function, they are limited in CLIS patients. On the other hand, fNIRS-based BMIs have facilitated communication for individuals in the most severe stages of ALS, providing hope for enhanced quality of life.

The electroencephalography (EEG) based BMI's main task is to restore communication and control for individuals with ALS. These BMIs employ EEG to locate and interpret brain signals associated with movement. Through decoding these signals, the BMIs enable the signal to output desired physical actions. These signals allow one's mind to control assistive technology, proving autonomous control over assistive technology. This technology enhances the independence of individuals with ALS. The cognitive abilities needed to interact with the environment are restored.

Meanwhile, Functional Near-Infrared Spectroscopy (fNIRS) based BMIs work through decoding neural activity. They achieve this through measuring changes in blood oxygenation in the brain. These are non-invasive BMIs, unlike EEG. They work by shining near-infrared light into the scalp, which penetrates the skull and interacts with oxygenated and deoxygenated hemoglobin in the brain's blood vessels. Through detecting variations in light, the BMI maps brain activity. Finally, this information is decoded and used to control external devices such as prosthetics or computer devices. fNIRS-based BMIs are promising for individuals with motor disabilities or conditions like paralysis as they serve to regain control and improve quality of life through thought-based communication and control.

One of the downsides of fNIRS is that they provide lower spatial resolution compared to other invasive BMIs like EEG since they only capture visual information from outside the brain. However, since they are non-invasive, the technology is more accessible and safer to implement.

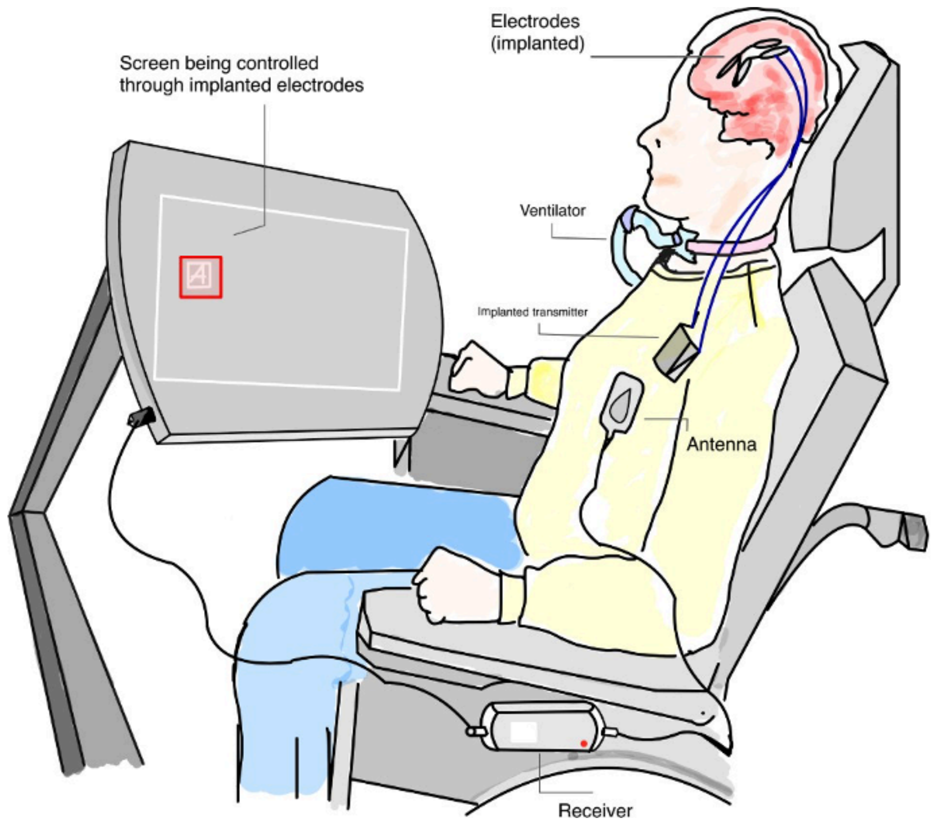

Figure 3. EEG-Based Brain-Machine Interfaces for Mobility and Communication. Combination for emplace electrodes and EEG based BMIs not only provide mobility through a wheelchair. This also connects with compatible tablets and computers giving autonomous control over the software.

2.13 Prosthetics

Prostheses are substitutes for parts of the body lost due to accidents, amputation, or birth defects. Types of prosthetics include arm and leg prostheses that fit over joints, artificial eyeballs, and hearing aids.

The way BMI is incorporated to develop new prosthetics, specifically neural prosthetics, is by recording signals from neuron populations and decoding the signals through mathematical algorithms. They then translate the intended action into physical limb movement.[15] Specific feedback calls like somatosensory feedback are used to provide a more natural sensation for prosthetics.

Somatosensation is a system of biological organs that respond to inputs and body states. The basis of this paradigm makes it so that the prosthetic user can use patterns of intensity and frequency of stimulation that are critical to perceived sensation. Benefits to using such a system is true embodiment of the limb; normal motor function; decrease in negative psychological impact of limb loss.[14,15]

2.2 Cognitive Impairments

2.21 Memory

While BMI technology has traditionally focused on restoring or enhancing sensory perceptions and muscular abilities, scientists are now venturing into a new realm of BMIs. These emerging technologies expand mobile conditions and incorporate implanted computers to amplify the formation and retrieval of memories within the brain.[16] Following aging or memory related diseases such as dementia and Alzheimer's, certain regions of the brain become slower due to a reduction in both neurotransmitters and blood flow to these areas.[17]

Following this trajectory, developers of BMI have utilized non-invasive BMIs.[18] Electromagnetic stimulation and biofeedback techniques as a part of a rehabilitation strategy to adjust brain activity. In addition, by focusing on specific brain wave patterns in the alpha and theta band regions, scientists can predict memory performance and enhance episodic memory. This usage of the technology is especially helpful as episodic memory - the long-term memory associated with previous experiences and associated emotions[19] - is the memory system that is most rapidly affected in response to both normal and unhealthy aging. Furthermore, electrophysiological signals could be connected to particular behavioral conditions whereby altering the timing of specific stimuli could enhance memory encoding. In other words, if these signals can serve as a "memory enhancement" just before engaging in specific tasks, elderly patients could give themselves a cognitive boost before remembering where they parked their car or comprehending their physician's instructions for medication use. Such technologies have the potential to allow patients with pathological memory loss the ability to perform daily life activities.

The use of BMI and neuroengineering technologies to resolve memory decline serves almost as a cognitive prosthesis, which is specifically useful for patient populations that need restoring their ability to form new long term-memories, especially after the natural process of aging or post-Alzheimer's disease.

2.22 Communication and Speech Impairments

Individuals affected by neurological conditions like brainstem stroke or ALS (*4.2 Paralysis*) often encounter profound difficulties with both their mobility and their speech functions.[20] For the latter, in some instances, these patients may experience a total inability to communicate verbally, a condition known as locked-in syndrome. To address this condition, researchers and engineers have worked on speech-based BMI programs to resolve such speech-based cognitive issues and ultimately improve communication disabilities.

One such example of this speech-based BMI program is a technology called a neuroprosthesis, which is an approach that decodes words and sentences directly from the cerebral cortical activity of impaired individuals. This technology involves surgically placing a high-density electrode on the outermost layer of the sensorimotor cortex, which is the part of the brain most responsible for controlling speech and having the patient attempt to speak with computer models connected.[21] As the participant attempts to articulate words from a list of basic vocabulary words, advanced deep-learning algorithms and computer models recognize and categorize words based on patterns in the brain activity. Using these computational models and a natural-language model that predicted the likelihood of the next word based on the words preceding it, the participants' words are translated into complete sentences.[22]

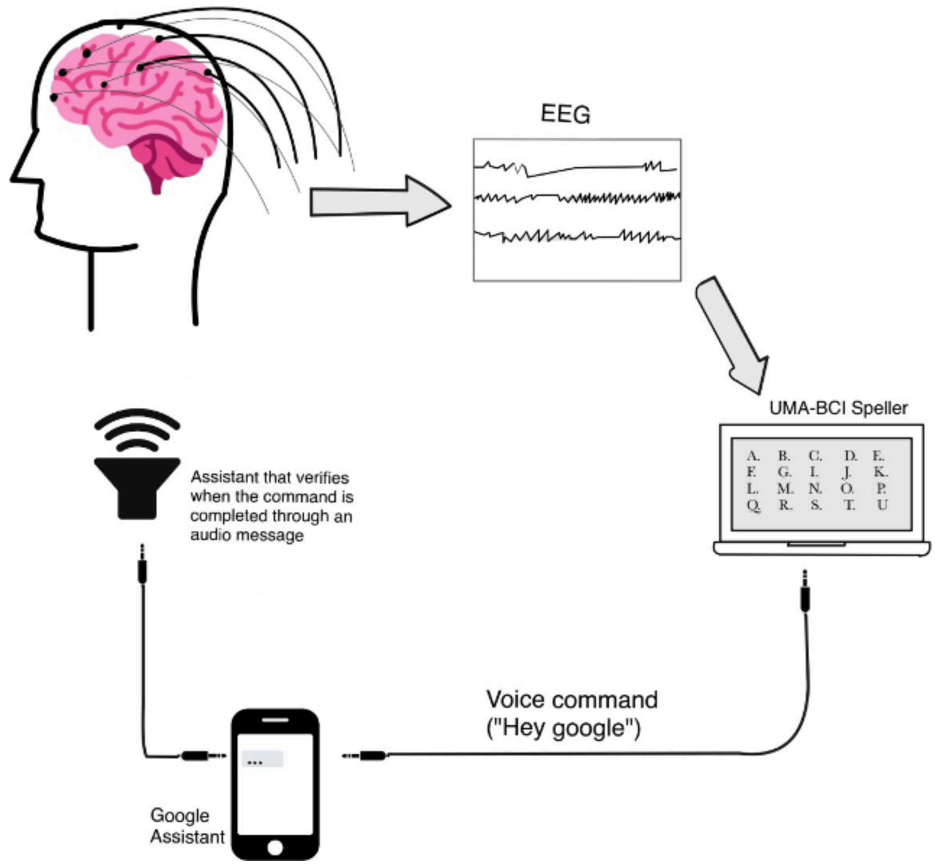

Figure 4. Advanced Neuroprosthetics for Speech Communication. Invasive BMI systems record accurate speech data through EEGs which are converted to words via UMA- BCI (University of Málaga-Brain-Computer Interfaces). Voice assistants like Google, Siri and Alexa are used for voice commands.

Though this technology is limited to vocabulary that is not very advanced, future directions in the field are working on mitigating this and expanding current technologies to include vocabulary lists with over 150,000 words with less than 9% error.[23] Additionally, when looking at these technologies that are directly related to the brain and speech, the implications of their value from an ethical standpoint must be considered. Though neuroprosthetics for speech decoding have the potential to inform consent and capacity - allow for agency and consent to medical treatment - this technology, for the same reason, may cause harm.[24] Neurotechnology-mediated communication can pose a risk to privacy, and in the case of defamation, threats, or harassment that is recorded from the participant, poses the question of whether or not they should be held responsible.[25]

These technologies, as powerful as they are in showing feasible paths for restoring rapid communication with those with communication disabilities, must be tweaked to account for both ethical and practical concerns as the technology advances.

2.3 Life-Enhancing Technologies

2.31 Home Improvement and Life Enhancing BMI Technologies

In order to help mitigate the effects of these impairments on the populations they affect, developers and businesses have incorporated artificial intelligence (AI) technology and electronics with home improvement tools to ease daily life functions. Whether its voice controlled speakers, AI cellphone assistants, or clap activated lights, the use of BMI and neuroengineering take home improvement advancements to a new level.

Building on this foundation of technological innovation, BTC (Brain to Thing Communication) represents a significant leap forward. BTC is a system that establishes direct connection from the human brain to outside devices such as TV's and other smart objects. This development has been helpful, as it can improve the lives of those disabled or advance home improvement in general.

The features of the BTC system consists of nearby smart objects that will be embedded with systems running sensing and actuation services. This makes the system aware of where the subject is around the house and adjusts accordingly. In fact, users can access the system throughout their daily lives no matter what and can remotely send brain commands via the application. In other words, patients with paralysis can perform different applications (control a wheelchair, nursing bed, lights, TV, and phone) inside a room through BMI based on biological signals (ie. left eye blink, right eye blink, eyebrow raise).[26]

Nevertheless, these technologies do come with various challenges. First, real-time EEG signal processing can pose difficulties whereby all commands should be processed in real time in order for the system to validate the action request. Secondly, while previous studies have demonstrated the accuracy of these prototypes, it is crucial to acknowledge that the system still has limitations in distinguishing specific patterns that differentiate user actions and requests. This is an area that requires significant improvement in the technology in the years to come.[27]

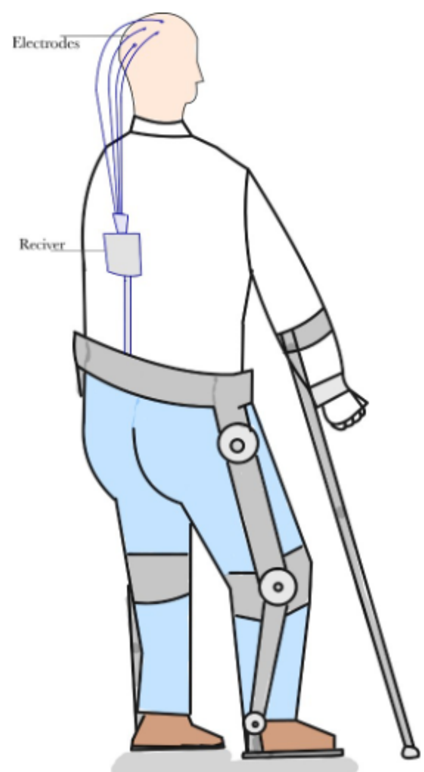

Figure 5. Enhancing Mobility with Assistive Exoskeletons. Assistive Exoskeleton is one of the examples of life-enhancing technologies. With the use of non-invasive BMI's the suit increases mobility in the elderly and heavily reduces the risk of critical falls.

2.4 Literature Review Summary

Author and Date	Participants	Target	Technological Area of Study	Results
MOBILITY IMPAIRMENTS				
Assessment of the Efficacy of EEG-Based MI-BCI With Visual Feedback and EEG Correlates of Mental Fatigue for Upper-Limb Stroke Rehabilitation, Foong et. al, 2020	Eleven stroke patients underwent nBETTER therapy, incorporating EEG-based motor imagery technology with standard arm therapy.	To evaluate the combined therapy's effect on upper-limb stroke rehabilitation as participants mentally moved their affected arm towards a target.	BMI and stroke.	Significant FMA improvement at weeks 6 and 24, with positive frontal-central BMI correlations in stroke rehabilitation.
COGNITIVE IMPROVEMENT				
Neurofeedback training with a motor imagery-based BCI: neurocognitive improvements and EEG changes in the elderly, Gomez-Pilar, 2016	63 participants aged 60+ were divided into control and experimental groups using neurofeedback training with a motor imagery-based BCI.	To determine if significant differences in age-related cognitive functions exist.	EEG-based BMIs' ability to increase cognitive function and memory amongst elderly.	By combining hand motor imagery and memory tasks, participants saw significant improvements in visuospatial, oral, memory, and intellectual areas
Neuroprosthesis for Decoding Speech in a Paralyzed Person with Anarthria, Moses, 2021	One study participant was affected by ALS so they can no longer speak intelligibly.	To demonstrate a speech-to-text BMI that records spiking activity and translates this to attempted speech articulation	BMI and communicatio n disabilities, such as speech impairment post paralysis.	Participants achieved a 9.1% word error rate on a 50-word vocabulary and a 23.8% word error rate on a 125,000-word vocabulary.
HOME IMPROVEMENT				
Non-invasive Control of a Intelligent Room Using EEG Signals, Bolanos et. al, 2021	5 healthy people and 5 paralyzed patients.	Motor-disabled individuals into a smart room, & allowing control of devices through a BMI.	Quality of life enhancements for paralyzed people.	Average accuracy for smart home controls was 97.5% for healthy patients and 83.6% for paralysis patients

Table 1. Literature Review Study Examples of Related Work for BMI Applications Organized by Mobile, Cognitive, and Home Improvement Technologies. The table provides an overview of key findings and their implications for advancing BMI research.

3. Discussion

3.1 Key Findings and Implications of Research

In terms of stroke rehabilitation, BMIs allow individuals with limited mobility and communication abilities to regain independence. For those with full paralysis, EEG-based BMIs provide communication and control options for ALS patients, while fNIRS-based BMIs offer potential for those in a completely locked-in state. For this reason, both invasive and non-invasive approaches have shown improvements in motor function, but challenges remain, including the need for further clinical testing, algorithm refinement, and affordability concerns.

From the cognition standpoint, emerging BMI technologies are targeting memory improvement, especially for individuals dealing with memory-related diseases like Alzheimer's. Non-invasive approaches, such as electromagnetic stimulation and biofeedback, aim to enhance episodic memory and cognitive function. Meanwhile, speech-based BMIs have the potential to restore communication for individuals with severe speech disabilities. These technologies can decode words and sentences directly from brain activity, allowing patients to express themselves. However, ethical concerns related to privacy, consent, and accountability must be addressed as these technologies advance.

Lastly, BTC systems enable direct communication between the brain and external devices, offering the potential to both enhance and improve the lives of individuals with disabilities and advance home automation.

3.2 Limitations

As mentioned, BMIs hold great potential to revolutionize the way we interact with technology and understand the human brain. However, BMIs are not without their limitations, which span economic, ethical, and scientific domains.

First, BMIs are intricate systems that depend on knowledge of the human brain, as well as the creation of incredibly sensitive hardware and software. The need for better signal processing algorithms to increase the accuracy and reliability of BMIs is one scientific challenge among many. Furthermore, significant obstacles to research studies are posed by the variability of brain activity and the possibility of signal noise. Concerns about potential risks and side effects are also raised due to the fact that the long-term effects of brain-computer interfaces are still not fully understood.[28]

Second, a primary limitation of BMIs is their cost. Developing and deploying BMI technology is expensive, making it inaccessible to many individuals and institutions. The economic barriers limit the widespread adoption of BMIs, particularly for medical purposes. Patients with neurological disorders who could benefit from BMIs often struggle to afford the technology, creating a disparity in access to potentially life-changing treatments. Addressing these economic challenges through cost reduction and better funding mechanisms is a pressing concern for BMI development.[29]

Third, ethical dilemmas surrounding BMIs are significant and multifaceted. For instance, BMIs raise significant ethical issues related to defending the agency of patients who may not have full cognitive ability or the capacity to provide informed consent. Protecting the rights and dignity of individuals with cognitive impairments is a crucial concern. Ensuring that BMIs are used to enhance the quality of life of these patients without infringing on their autonomy is paramount. Developing ethical guidelines and regulations that prioritize the welfare and agency of vulnerable populations is essential.[30] Another ethical concern arises when considering individuals' perspectives on invasive procedures. Invasive techniques have more associated risks because of the requirement for surgery, as well as the possibility of scarring.[31]

Despite these challenges, the development of BMIs continues to progress. Efforts are underway to reduce costs, establish ethical guidelines, and advance scientific research.

4. Future Directions

BMIs hold great potential for enhancing the quality of life for individuals with cognitive or mobility-based impairments, motivating sustained innovation in this field. BMIs are expected to witness substantial enhancements in terms of control precision, communication speed, and versatility. These advancements will likely involve the integration of cutting-edge artificial intelligence (AI) techniques for more accurate signal processing and decoding algorithms, offering individuals with disabilities more practical and intuitive ways to interact with the external world. Moreover, ongoing research will continue to focus on neurorehabilitation, where AI-powered BMIs can revolutionize the recovery process for individuals affected by neurological disorders. Personalized rehabilitation programs, guided by AI and responsive to patients' unique needs and progress, could significantly improve the effectiveness of recovery exercises.

Additionally, the development of neuroprosthetics, including limbs and sensory devices, will drive future BMI research. These devices aim to replicate the natural functions of missing or damaged body parts, and AI will play a pivotal role in making them adaptable and responsive to users' movements. Moreover, as BMIs expand beyond medical applications, they have the potential to transform human cognition. Researchers are exploring ways to use BMIs, enhanced by AI, for cognitive augmentation, memory improvement, and knowledge transfer, opening up new horizons for human potential. Overall, the future of BMIs is not only exciting but also transformative, offering unprecedented possibilities to enhance human lives, both in healthcare and daily interactions.

4. Conclusion

The field of BMIs and neuroengineering holds great power for improving the lives of individuals with cognitive and mobility impairments. Continued research and development are essential to address technical challenges, refine algorithms, and improve the affordability and accessibility of BMI technologies. The integration of artificial intelligence (AI) with BMIs presents new possibilities for enhancing the effectiveness of these technologies and expanding their applications. Future studies should focus on long-term outcomes, safety, and usability to ensure that BMIs and neuroengineering technologies are effective and practical solutions for patients.

5. Acknowledgements

We would like to acknowledge Berkeley Pharma Tech for connecting us with the resources and the outlet to discuss our findings in this review paper.

References

1. Azevedo FA, Carvalho LR, Grinberg LT, et al. Equal numbers of neuronal and nonneuronal cells make the human brain an isometrically scaled-up primate brain. *J Comp Neurol.* 2009;513(5):532-541. doi:10.1002/cne.21974.

2. Lebedev MA, Nicolelis MAL. Brain-machine interfaces: From basic science to neuroprostheses and neurorehabilitation. *Physiol Rev.* 2017;97(2):332-339. doi:10.1152/physrev.00027.2016.

3. Shih JJ, Krusienski DJ, Wolpaw JR. Brain-computer interfaces in medicine. *Mayo Clin Proc.* 2012;87(3):268-279. doi:10.1016/j.mayocp.2011.12.008.

4. Kawala-Sterniuk A, Browarska N, Al-Bakri A, et al. Summary of over fifty years with brain-computer interfaces—a review. *Brain Sci.* 2021;11(1):43. doi:10.3390/brainsci11010043.

5. Davidoff EJ. Agency and accountability: Ethical considerations for brain-computer interfaces. *Rutgers J Bioeth.* 2020;11:9-20.

6. Lebedev MA, Nicolelis ML. Brain–machine interfaces: Past, present and future. *Prog Brain Res.* 2006;29(9):90. Accessed October 27, 2023. https://citeseerx.ist.psu.edu/document.

7. Raspopovic S, Stanisa L. Restoring natural sensory feedback in real-time bidirectional hand prostheses. *Sci Transl Med.* 2014;31(1):1. doi:10.1126/scitranslmed.3006820.

8. Zhang X, Ma Z, Zheng H, et al. The combination of brain-computer interfaces and artificial intelligence: Applications and challenges. *Ann Transl Med.* 2020;8(11):712. doi:10.21037/atm.2019.11.109.

9. National Heart, Lung, and Blood Institute. Stroke. *NHLBI website.* Accessed October 27, 2023. https://www.nhlbi.nih.gov/health/stroke.

10. Cleveland Clinic. Stroke. *Cleveland Clinic website.* Accessed October 27, 2023. https://my.clevelandclinic.org/health/diseases/5601-stroke.

11. Cervera MA, Soekadar SR, Ushiba J, et al. Brain-computer interfaces for post-stroke motor rehabilitation: A meta-analysis. *Ann Clin Transl Neurol.* 2018;5(5):651-663. doi:10.1002/acn3.544.

12. López-Larraz E, Sarasola-Sanz A, Irastorza-Landa N, Birbaumer N, Ramos-Murguialday A. New concepts in stroke rehabilitation. *NeuroRehabilitation.* 2018;43(1):77-97. doi:10.3233/NRE-172394.

13. Healthdirect Australia. Prostheses. *Healthdirect website.* Accessed October 27, 2023. https://www.healthdirect.gov.au/prostheses.

14. Vidal GW, Rynes ML, Kelliher Z, Goodwin SJ. Review of brain-machine interfaces used in neural prosthetics with new perspective on somatosensory feedback through method of signal breakdown. *Scientifica (Cairo).* 2016;2016:8956432. doi:10.1155/2016/8956432.

15. Tyler DJ. Neural interfaces for somatosensory feedback: Bringing life to a prosthesis. *Curr Opin Neurol.* 2015;28(6):574-581. doi:10.1097/WCO.0000000000000266.

16. Jangwan NS, Ashraf GM, Ram V, et al. Brain augmentation and neuroscience technologies: Current applications, challenges, ethics and future prospects. *Front Syst Neurosci.* 2022;16:1000495. doi:10.3389/fnsys.2022.1000495.

17. Tarumi T, Zhang R. Cerebral blood flow in normal aging adults: Cardiovascular determinants, clinical implications, and aerobic fitness. *J Neurochem.* 2018;144(5):595-608. doi:10.1111/jnc.14234.

18. Belkacem AN, Jamil N, Palmer JA, Ouhbi S, Chen C. Brain-computer interfaces for improving the quality of life of older adults and elderly patients. *Front Neurosci.* 2020;14:692. doi:10.3389/fnins.2020.00692.

19. Burke JF, Merkow MB, Jacobs J, Kahana MJ, Zaghloul KA. Brain-computer interface to enhance episodic memory in human participants. *Front Hum Neurosci.* 2015;8:1055. doi:10.3389/fnhum.2014.01055.

20. Khalili-Ardali M, Wu S, Tonin A, Birbaumer N, Chaudhary U. Neurophysiological aspects of the completely locked-in syndrome in patients with advanced amyotrophic lateral sclerosis. *Clin Neurophysiol.* Published March 17, 2021. https://www.sciencedirect.com/science/article/pii/S1388245721000341.

21. Metzger SL, Littlejohn KT, Silva AB, et al. A high-performance neuroprosthesis for speech decoding and avatar control. *Nature.* 2023;620:1037-1046. doi:10.1038/s41586-023-06443-4.

22. Moses DA, Metzger SL, Liu JR, et al. Neuroprosthesis for decoding speech in a paralyzed person with anarthria. *N Engl J Med.* 2021;385:217-227. doi:10.1056/NEJMoa2027540.

23. Willett FR, Kunz EM, Fan C, et al. A high-performance speech neuroprosthesis. *Nature.* 2023;620:1031-1036. https://www.nature.com/articles/s41586-023-06377-x. Accessed October 27, 2023.

24. Chandler JA, Van der Loos KI, Boehnke S, et al. Brain-computer interfaces and communication disabilities: Ethical, legal, and social aspects of decoding speech from the brain. *Front Hum Neurosci.* 2022;16:841035. doi:10.3389/fnhum.2022.841035.

25. Klein E, Kinsella M, Stevens I, Fried-Oken M. Ethical issues raised by incorporating personalized language models into brain-computer interface communication technologies: A qualitative study of individuals with neurological disease. *Disabil Rehabil Assist Technol.* 2022. doi:10.1080/17483107.2022.2146217.

26. Sun KT, Hsieh KL, Syu SR. Towards an accessible use of a brain-computer interfaces-based home care system through a smartphone. *Comput Intell Neurosci.* 2020;1520:1-1710. doi:10.1155/2020/1843269.

27. Teles A, Cagy M, Silva F, et al. Using brain-computer interface and Internet of Things to improve healthcare for wheelchair users. *Proc Int Conf Mobile Ubiquitous Comput.* 2017:92-94.

28. Mridha MF, Das SC, Kabir MM, et al. Brain-computer interface: Advancement and challenges. *Sensors.* 2021;21(17):5746. doi:10.3390/s21175746.

29. Burwell S, Sample M, Racine E. Ethical

aspects of brain-computer interfaces: A scoping review. *BMC Med Ethics.* 2017;18(1):22. doi:10.1186/s12910-017-0220-y.

30. Bergeron D, Iorio-Morin C, Bonizzato M, et al. Use of invasive brain-computer interfaces in pediatric neurosurgery: Technical and ethical considerations. *J Child Neurol.* 2023;38(3-4):223-238. doi:10.1177/08830738231167736.

31. Fiani B, Reardon T, Ayres B, Cline D, Sitto SR. An examination of prospective uses and future directions of Neuralink: The brain-machine interface. *Cureus.* 2021;13(3):e14192. doi:10.7759/cureus.14192.