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MINI REVIEW: THE APPLICATION OF BRAIN-COMPUTER INTERFACES IN ROBOTIC THERAPY

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ABSTRACT

The idea of robotic therapy has been considered as a possible rehabilitation strategy to facilitate recovery of the patients with disability and it can represent an efficient treatment. Brain-computer interface (BCI) is known as an advanced technology with great potential in therapeutic and assistive robots. This paper is presented to review the application of BCI in rehabilitation robotic systems through the combination of BCI with electroencephalography (EEG) and functional electrical stimulation (FES). For this purpose, the basic concept of each of BCI, EEG, and FES is introduced to give a general view of their function. In addition, the application of EEG-BCI and FES-BCI systems in therapeutic and assistive treatments is showed by providing a summary of different researches for each field. In the end, this document is terminated with a discussion about the arguments behind the studied topics and the future directions of advances in robotic therapy.

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1. INTRODUCTION

Stroke is a significant reason for acquired disability in the world, which can end with substantial neural damage or even death. It is a major reason for long-term disabilities and may lead to loss of movement, coordination, sensation, and difficulties with activities of daily living Chung (2017); Louie and Eng (2016); Mozaffarian et al. (2016); Rodgers et al. (2019). Strokes in the elderly people may reduce their mobility and lead them to fewer independent lives and poor quality of life; even though they normally have physical deterioration and weakness, which imposes a heavy responsibility on the social health care system B. Chen et al. (2020); H. Kim et al. (2019). Also, millions of people experience stroke worldwide each year, and many of these patients have to deal with some level of permanent hemiparesis resulting from the damage to neural tissues Harcum et al. (2019); H. Kim et al. (2019). These stroke survivors and the elderly are beginning recognition of the importance of rehabilitation methods as a lifelong practice because they cannot do daily activities independently. However, traditional manual therapy methods mostly depend on the experience of the therapist and they often do not meet the requirements of high-intensity and repetitive training Zhou et al. (2013).

Robotic therapy is an advanced technique of physical therapy, through which patients practice their paretic limb by resorting to or resisting the force offered by a robotic system to enable the implementation of highly repetitive, intensive, adaptive, and quantifiable physical training Basteris et al. (2014); J. Chen et al. (2020); Duret et al. (2019). The application of rehabilitation robots can release the doctors and therapists from heavy training tasks and also assess the patient's functional performance by measuring kinetic movement parameters. Due to the benefits of its accuracy and reliability, rehabilitation robots can provide an effective way to improve the result of stroke or postsurgical rehabilitation Simonetti et al. (2016); Zhang et al. (2017). Noticeably, robotic therapy can modify motor functional recovery with improved movement completion time, more suitable employment of joint muscle groups, smoothness of motion, and improved inter-joint coordination of joints de Sousa et al. (2018); Prange et al. (2015).

The robotic therapy equipment can be designed for recovery in the lower limb and/or upper limb. Lower limb rehabilitation robots can be used as assistive devices to allow individuals with complete spinal cord injury to walk Sale et al. (2012). These devices may include a mechanism for steps posture and weight alleviation controlling to assist patients in simulating healthy individual's footsteps and practicing leg muscles Díaz et al. (2011). Also, upper limb rehabilitation robots consist of methods to rehabilitate the hand, wrist, elbow, and shoulder G. Kim et al. (2017). Using these devices for sensorimotor training can improve motor control of the shoulder and elbow and upper limb functional outcomes Mehrholz et al. (2015); Veerbeek et al. (2017). Based on the mechanical structure rehabilitation robotic devices can be divided into end-effector and exoskeleton systems Duret et al. (2019); Yue et al. (2017); Zhang et al. (2017). An end-effector device is often external to the body of patients, and it can generate the required force to the end of the user's extremity to help or resist the motion Gopura et al. (2016). These systems ensure that the patient is restricted to the specified range of motions, by controlling the paths along which their joints can move and maneuver. Also, they can apply resistance to the patient in the same alignment as they are experiencing in a virtual reality simulation to provide accurate feedback data McConnell et al. (2017); Mehrholz et al. (2015). An exoskeleton device can be worn on the body of patients. The joint and links of the robot have a direct connection with the human joints and limbs, respectively Gopura et al. (2016). Also, the portability of the exoskeleton has made it a good choice for patients in the later period of stroke when they can practice and train themselves at home Bos et al. (2016).

This paper is presented to review the application of brain-computer interface (BCI) in the development of rehabilitation robotic systems. Accordingly, at first, a conceptual description of BCI is provided to be used in robotic therapy. Then, two methods, including electroencephalography and functional electrical stimulation, are introduced to review their basic functions. Also, a summary of examples of some related research studies in therapeutic and assistive methods are represented. In the end, the arguments behind the mentioned fields are discussed and a possible configuration of future advanced technologies in robotic therapy is suggested.

2. METHODS

The advances in robotic technology had made it possible to form new rehabilitation systems, which can increase the efficiency and develop the range of application of therapeutic devices. ”Brain-computer interface” is one of these technologies.

2.1 BRAIN-COMPUTER INTERFACE

Brain-computer interface (BCI) is an advanced method that connects our natural brain with and an external device, providing a new communication channel for brain signals to control external devices without using the natural neuromuscular routes. BCIs are often directed at researching, mapping, assisting, augmenting, or repairing human cognitive or sensory-motor functions He et al. (2015); Krucoff et al. (2016). By detecting the brain's signals and interpreting them, BCI allows generating control commands for external devices. The detection of the brain signals is performed either by the recording of its electrical activity or the related magnetic activity Lange et al. (2016). A BCI-based system contains at least four main steps: (1) extracting signals from the nervous system, (2) decoding the signals to predict user intent, (3) generating an output to affect the subject's environment, and (4) providing a feedback system to help the user refine the output Krucoff et al. (2016). Figure 1 shows how BCI operates in a system and its input and output signals.

The benefit of BCI is the independence from any remaining muscular functions, which means that muscle fatigue is irrelevant. So, it can be used to restore lost or impaired functions of patients severely disabled by various devastating neuromuscular disorders or patients with damaged nervous systems Lange et al. (2016); Lazarou et al. (2018). BCI can promote long-lasting recovery in the motor function of chronic stroke patients with severe myasthenia and represents a promising strategy in severe stroke neuro-rehabilitation Ramos-Murguialday et al. (2019). Combined with BCI, the signal of the brain evoked by the individuals' spontaneous motor imaginary can be extracted and classified to directly control the robot. With this collaboration, robotic therapy can discover an artificial pathway to replace the normal motor pathway of humans Teo and Chew (2014).

BCIs have the potential to provide two key benefits to disabled users: an alternate means of communication, and the ability to independently move around in and inter-

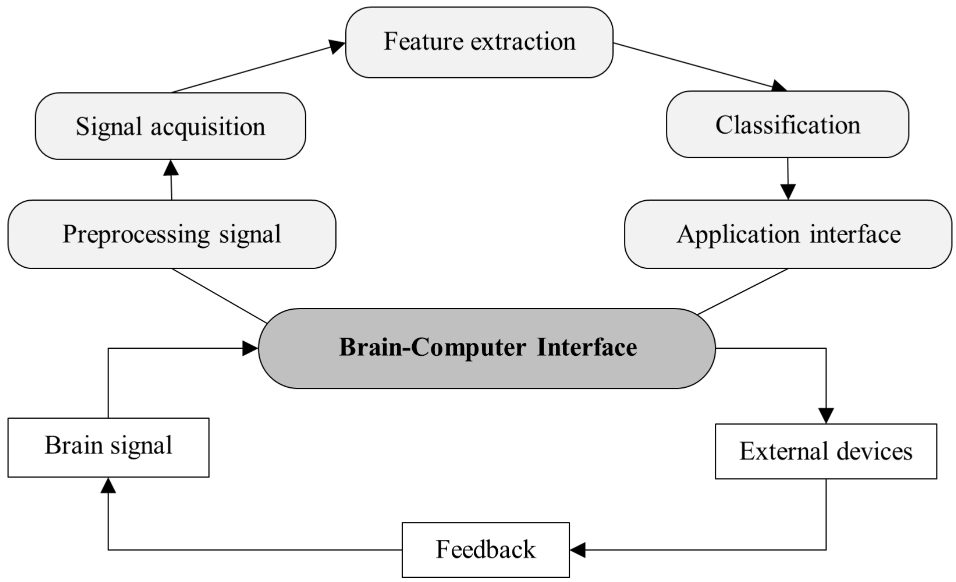

Figure 1 The functionof BCI in a system

act with their environment He et al. (2015). The use of BCI in stroke rehabilitation can be divided into two main approaches: a monitoring mechanism, with recorded brain signals serving as feedback data for concentration levels of the therapeutic practice; and a control framework in which an artificial actuator is driven at demand Maier et al. (2019).

2.2 ELECTROENCEPHALOGRAPHY

Non-invasive BCIs relate to methods that extract brain signals without surgical procedures. The experimental setup ranges from large and relatively expensive options, like magneto-encephalography (MEG), to lightweight and inexpensive methods, like electroencephalography (EEG). Due to its availability and ease of use, EEG is widely used in clinical stroke rehabilitation He et al. (2015); Yuan and He (2014). This method is performed by measuring the electric field on the patient's scalp through electrodes. The signal of the patient is not enough to actuate the motion of the paretic limb, but it is strong enough for the data acquisition instruments to collect Lange et al. (2016). EEG-based BCI operates by establishing a closed-loop neural interface. In other words, a BCI system uses raw functional cortical activity generated by EEG and translates it into a classified device command Kreilinger et al. (2012); Soekadar et al. (2015). Also, signal input is amplified and processed by a regression model that extracts particular amplitude changes or features and accounts for signal noise Kasuga et al. (2015); Young et al. (2014). With real-time processing, the reduced representation of brain activity is effectively translated into an output or feedback modality, often one that allows the desired task to be performed more easily Remsik et al. (2016). Some features of EEG-based BCI systems are:

- To monitor and control brain activity of patients to improve their neural representation
- To facilitate arm mobilization with higher motor gain for paralyzed arms and hands
- Movement intention decoding performance and motor recovery
- To engage the patients with tasks and acquire cortical signal of their imagination of a movement

By using EEG-based BCI, voluntary movement or motion attempt of the limb activates the primary sensorimotor section in the brain, which is characterized by specific brain rhythms over the hemisphere contralateral to the limb in use Ang et al. (2015). EEG signals can be controlled by BCI to aid the patient, either by bypassing a physical impairment in the ability to control the limb or by highlighting engagement with a movement Ron-Angevin et al. (2017). In Barsotti et al. (2015); Frisoli et al. (2012) , EEG was used as a data acquisition system to record activity during BCI-training to support tasks like preparation of movement, reaching, grasping, and releasing. This method was also used to study the effect of BCI control of passive motion for stroke patients while they were imagining a reach and grasp movement using the affected limb Lu et al. (2020); Pereira et al. (2018). EEG-based BCI was used in Chowdhury et al. (2019) to estimate the quality of engagement of a patient with tasks by measuring the relationship between the brain and the muscle signals. In Spüler et al. (2018), the effects of decoding performance on movement intention in a BCI system was studied by varying the cortical source of activity and the EEG frequency band in stroke patients.

2.3 FUNCTIONAL ELECTRICAL STIMULATION

Functional electrical stimulation (FES) is a subtype of neuromuscular electrical stimulation, which uses low-energy electrical pulses to artificially generate body movements. It can be used to generate muscle contraction in paralyzed limbs to produce functions such as grasping, walking, and standing Moineau et al. (2019). In FES, the electrode mainly operates as a conductor, sending electrical charge from a power supply over the tissue. When this applied voltage between the active electrode and a second electrode generates an electric field, charge transfer occurs, which as a result, forces electrical charge to flow (Ho et al. (2014) Ho et al., 2014). Then, this electrical current elicits a response in excitable cells including neurons. Cochlear implants to restore hearing, phrenic pacemakers that aid respiration, cardiac pacemakers to ensure cardiac function, and deep brain stimulation to control tremors due to Parkinson's disease are examples of applications of electrical stimulation systems (Marquez-Chin and Popovic (2020)).

Nowadays, FES-BCI systems are increasingly being explored as potential rehabilitation tools for improving the function of partially impaired limbs (Do et al. (2011)). FES can use real-time feedback of BCI signal input to optionally administer feedback responses of treatment only when the correct brain signals are discovered. Using FES in robotic therapy can lead to a better realization of the recovery of limb function (Rong et al. (2012)). Some features of FES-BCI systems are:

- To generate muscle contractions and subsequent limb movement
- To provide functional recovery and elicit motor recovery
- To adjust the intensity of the electrical stimuli to achieve more precise movements
- To improve functional mobility and range of motion of flexion and extension muscles exercises

Neuro-rehabilitation methods employing FES to maneuver the paralyzed muscles can postpone or prevent many secondary medical complications and modify functional independence by providing a means to exercise and practice physical obstacles Ho et al. (2014). These methods can be used to improve functional mobility and range of movement of paretic stroke patients T. Kim et al. (2016). FES-BCI training can be beneficial on shoulder reduction and active movements by facilitating motor recovery Jang et al. (2016). In Grimm et al. (2016), the effects of this method were examined on the range of motion and cortical modulation in stroke patients who performed wrist flexion and extension exercises. BCI–FES can provide high functional recovery in patients with a high degree of residual mobility in arm and hand function and also elicit motor recovery in stroke patients Biasiucci et al. (2018). To perform daily living activities, BCI with a neural decoder can be used to produce coordinated reaching andgrasping movements and FES to generate muscle contractions and subsequent limb movement Ajiboye et al. (2017). In Bockbrader et al. (2019), the ability of FES-BCI was examined in evoking greater wrist extension strength and controlling translation, orientation, and hand shape of robotic limbs.

3. DISCUSSION

Robotic therapy is known as an efficient rehabilitation technology to facilitate the recovery and treatment of patients with disabilities. BCI is an advanced technology with great potential in rehabilitation robots that can control external devices using brain signals. Accordingly, as it was reviewed in this paper, it can be defined a control loop for rehabilitation robots including BCI, EEG, and FES. In this loop, EEG, as a non-invasive method, provides brain signals for BCI. Then, BCI processes the acquired signals and controls the robotic device. Also, FES can be used as a part of this device to facilitate the movements of the limb. In addition, there are some methods, like virtual reality and augmented reality, which can provide visual and auditory feedback signals to be used in this loop. It is estimated that by the collaboration of BCI, EEG, and FES with a rehabilitation robotic system, even the patients with more serious disabilities can benefit an effective treatment.

REFERENCES

Ajiboye, A. B., Willett, F. R., Young, D. R., Memberg, W. D., Murphy, B. A., Miller, J. P., Walter, B. L., Sweet, J. A., Hoyen, H. A., Keith, M. W., Peckham, P. H., Simeral, J. D., Donoghue, J. P., Hochberg, L. R., & Kirsch, R. F. (2017). Restoration of reaching and grasping movements through brain-controlled muscle stimulation in a person with tetraplegia: a proof-of-concept demonstration. *The Lancet*, *389*(10081), 1821–1830. Retrieved from https://dx.doi.org/10.1016/s0140-6736(17)30601-3 10.1016/s0140-6736(17)30601-3

Ang, K. K., Chua, K. S., Phua, K. S., Wang, C., Chin, Z. Y., & Kuah, C. W. (2015). A Randomized Controlled Trial of EEG-Based Motor Imagery Brain-Computer Interface Robotic Rehabilitation for Stroke. *Clin EEG Neurosci*, *46*(4), 310–320.

Barsotti, M., Leonardis, D., Loconsole, C., Solazzi, M., Sotgiu, E., & Procopio, C. (2015). A full upper limb robotic exoskeleton for reaching and grasping rehabilitation triggered by MI-BCI. *IEEE International Conference on Rehabilitation Robotics (ICORR)*, 11–14.

Basteris, A., Nijenhuis, S. M., Stienen, A. H., Buurke, J. H., Prange, G. B., & Amirabdollahian, F. (2014). Training modalities in robot-mediated upper limb rehabilitation in stroke: a framework for classification based on a systematic review. *Journal of NeuroEngineering and Rehabilitation*, *11*(1), 111–111. Retrieved from https://dx.doi.org/10.1186/1743-0003-11-111 10.1186/1743-0003-11-111

Biasiucci, A., Leeb, R., Iturrate, I., Perdikis, S., Al-Khodairy, A., Corbet, T., Schnider, A., Schmidlin, T., Zhang, H., Bassolino, M., Viceic, D., Vuadens, P., Guggisberg, A. G., & d. R. Millán, J. (2018). Brain-actuated functional electrical stimulation elicits lasting arm motor recovery after stroke. *Nature Communications*, *9*(1), 2421–2421. Retrieved from https://dx.doi.org/10.1038/s41467-018-04673-z 10.1038/s41467-018-04673-z

Bockbrader, M., Annetta, N., Friedenberg, D., Schwemmer, M., Skomrock, N., Colachis, S., Zhang, M., Bouton, C., Rezai, A., Sharma, G., & Mysiw, W. J. (2019). Clinically Significant Gains in Skillful Grasp Coordination by an Individual With Tetraplegia Using an Implanted Brain-Computer Interface With Forearm Transcutaneous Muscle Stimulation. *Archives of Physical Medicine and Rehabilitation*, *100*(7), 1201–1217. Retrieved from https://dx.doi.org/10.1016/j.apmr.2018.07.445 10.1016/j.apmr.2018.07.445

Bos, R. A., Haarman, C. J., Stortelder, T., Nizamis, K., Herder, J. L., Stienen, A. H., & Plettenburg, D. H. (2016). A structured overview of trends and technologies used in dynamic hand orthoses. *Journal of NeuroEngineering and Rehabilitation*, *13*(1), 62–62. Retrieved from https://dx.doi.org/10.1186/s12984-016-0168-z 10.1186/s12984-016-0168-z

Chen, B., Zi, B., Qin, L., & Pan, Q. (2020). State-of-the-art research in robotic hip exoskeletons: A general review. *Journal of Orthopaedic Translation*, *20*, 4–13. Retrieved from https://dx.doi.org/10.1016/j.jot.2019.09.006 10.1016/j.jot.2019.09.006

Chen, J., Jin, Z., Yao, J., Wang, H., Li, Y., & Ouyang, Z. (2020). Influence of the intelligent standing mobile robot on lower extremity physiology of complete spinal cord injury patients. *Medicine in Novel Technology and Devices*, *7*, 100045–100045.

Chowdhury, A., Raza, H., Meena, Y. K., Dutta, A., & Prasad, G. (2019). An EEG-EMG correlation-based brain-computer interface for hand orthosis supported neuro-rehabilitation. *Journal of Neuroscience Methods*, *312*, 1–11. Retrieved from https://dx.doi.org/10.1016/j.jneumeth.2018.11.010 10.1016/j.jneumeth.2018.11.010

Chung, B. P. H. (2017). Effectiveness of robotic-assisted gait training in stroke rehabilitation: A retrospective matched control study. *Hong Kong Physiotherapy Journal*, *36*, 10–16.

de Sousa, D. G., Harvey, L. A., Dorsch, S., & Glinsky, J. V. (2018). Interventions involving repetitive practice improve strength after stroke: a systematic review. *Journal of Physiother-*

apy, *64*(4), 210–221. Retrieved from https://dx.doi.org/10.1016/j.jphys.2018.08.004 10.1016/j.jphys.2018.08.004

Díaz, I., Gil, J. J., & Sánchez, E. (2011). Lower-Limb Robotic Rehabilitation: Literature Review and Challenges. *Journal of Robotics*, *2011*, 1–11. Retrieved from https://dx.doi.org/10.1155/2011/759764 10.1155/2011/759764

Do, A. H., Wang, P. T., King, C. E., Abiri, A., & Nenadic, Z. (2011). Brain-Computer Interface Controlled Functional Electrical Stimulation System for Ankle Movement. *Journal of NeuroEngineering and Rehabilitation*, *8*(1), 49–49. Retrieved from https://dx.doi.org/10.1186/1743-0003-8-49 10.1186/1743-0003-8-49

Duret, C., Grosmaire, A.-G., & Krebs, H. I. (2019). Robot-Assisted Therapy in Upper Extremity Hemiparesis: Overview of an Evidence-Based Approach. *Frontiers in Neurology*, *10*, 412–412. Retrieved from https://dx.doi.org/10.3389/fneur.2019.00412 10.3389/fneur.2019.00412

Frisoli, A., Procopio, C., Chisari, C., Creatini, I., Bonfiglio, L., Bergamasco, M., Rossi, B., & Carboncini, M. (2012). Positive effects of robotic exoskeleton training of upper limb reaching movements after stroke. *Journal of NeuroEngineering and Rehabilitation*, *9*(1), 36–36. Retrieved from https://dx.doi.org/10.1186/1743-0003-9-36 10.1186/1743-0003-9-36

Gopura, R. A. R. C., Bandara, D. S. V., Kiguchi, K., & Mann, G. K. I. (2016). Developments in hardware systems of active upper-limb exoskeleton robots: A review. *Robotics and Autonomous Systems*, *75*, 203–220. Retrieved from https://dx.doi.org/10.1016/j.robot.2015.10.001 10.1016/j.robot.2015.10.001

Grimm, F., Walter, A., Spüler, M., Naros, G., Rosenstiel, W., & Gharabaghi, A. (2016). Hybrid Neuroprosthesis for the Upper Limb: Combining Brain-Controlled Neuromuscular Stimulation with a Multi-Joint Arm Exoskeleton. *Frontiers in Neuroscience*, *10*, 367–367. Retrieved from https://dx.doi.org/10.3389/fnins.2016.00367 10.3389/fnins.2016.00367

Harcum, S., Conroy, S. S., Boos, A., Ermer, E., Xu, H., Zhan, M., Chen, H., Whitall, J., Dimyan, M. A., & Wittenberg, G. F. (2019). Methods for an Investigation of Neurophysiological and Kinematic Predictors of Response to Upper Extremity Repetitive Task Practice in Chronic Stroke. *Archives of Rehabilitation Research and Clinical Translation*, *1*(3-4), 100024–100024. Retrieved from https://dx.doi.org/10.1016/j.arrct.2019.100024 10.1016/j.arrct.2019.100024

He, B., Baxter, B., Edelman, B. J., Cline, C. C., & Ye, W. W. (2015). Noninvasive Brain-Computer Interfaces Based on Sensorimotor Rhythms. *Proceedings of the IEEE*, *103*(6), 907–925. Retrieved from https://dx.doi.org/10.1109/jproc.2015.2407272 10.1109/jproc.2015.2407272

Ho, C. H., Triolo, R. J., Elias, A. L., Kilgore, K. L., DiMarco, A. F., & Bogie, K. (2014). Functional Electrical Stimulation and Spinal Cord Injury. *Physical Medicine and Rehabilitation Clinics of North America*, *25*, 631–654. Retrieved from https://dx.doi.org/10.1016/j.pmr.2014.05.001 10.1016/j.pmr.2014.05.001

Jang, Y. Y., Kim, T. H., & Lee, B. H. (2016). Effects of Brain-Computer Interface-controlled Functional Electrical Stimulation Training on Shoulder Subluxation for Patients with Stroke: A Randomized Controlled Trial. *Occup Ther Int*, *23*(2), 175–185.

Kasuga, S., Matsushika, Y., Kasashima-Shindo, Y., Kamatani, D., Fujiwara, T., Liu, M., & Ushiba, J. (2015). Transcranial direct current stimulation enhances mu rhythm desynchronization during motor imagery that depends on handedness. *Laterality: Asymmetries of Body, Brain and Cognition*, *20*(4), 453–468. Retrieved from https://dx.doi.org/

10.1080/1357650x.2014.998679 10.1080/1357650x.2014.998679

Kim, G., Lim, S., Kim, H., Lee, B., Seo, S., & Cho, K. (2017). Is robot-assisted therapy effective in upper extremity recovery in early stage stroke? -a systematic literature review. *Journal of Physical Therapy Science*, *29*(6), 1108–1112.

Kim, H., Cho, S., & Lee, H. (2019). Effects of passive Bi-axial ankle stretching while walking on uneven terrains in older adults with chronic stroke. *Journal of Biomechanics*, *89*, 57–64.

Kim, T., Kim, S., & Lee, B. (2016). Effects of Action Observational Training Plus Brain-Computer Interface-Based Functional Electrical Stimulation on Paretic Arm Motor Recovery in Patient with Stroke: A Randomized Controlled Trial. *Occup Ther Int*, *23*(1), 39–47.

Kreilinger, A., Kaiser, V., Breitwieser, C., Williamson, J., Neuper, C., & Müller-Putz, G. R. (2012). Switching between Manual Control and Brain-Computer Interface Using Long Term and Short Term Quality Measures. *Frontiers in Neuroscience*, *5*, 147–147. Retrieved from https://dx.doi.org/10.3389/fnins.2011.00147 10.3389/fnins.2011.00147

Krucoff, M. O., Rahimpour, S., Slutzky, M. W., Edgerton, V. R., & Turner, D. A. (2016). Enhancing Nervous System Recovery through Neurobiologics, Neural Interface Training, and Neurorehabilitation. *Frontiers in Neuroscience*, *10*, 584–584. Retrieved from https://dx.doi.org/10.3389/fnins.2016.00584 10.3389/fnins.2016.00584

Lange, G., Low, C. Y., Johar, K., Hanapiah, F. A., & Kamaruzaman, F. (2016). Classification of Electroencephalogram Data from Hand Grasp and Release Movements for BCI Controlled Prosthesis. *Procedia Technology*, *26*, 374–381. Retrieved from https://dx.doi.org/10.1016/j.protcy.2016.08.048 10.1016/j.protcy.2016.08.048

Lazarou, I., Nikolopoulos, S., Petrantonakis, P. C., Kompatsiaris, I., & Tsolaki, M. (2018). EEG-Based Brain–Computer Interfaces for Communication and Rehabilitation of People with Motor Impairment: A Novel Approach of the 21st Century. *Frontiers in Human Neuroscience*, *12*, 14–14. Retrieved from https://dx.doi.org/10.3389/fnhum.2018.00014 10.3389/fnhum.2018.00014

Louie, D. R., & Eng, J. J. (2016). Powered robotic exoskeletons in post-stroke rehabilitation of gait: a scoping review. *Journal of NeuroEngineering and Rehabilitation*, *13*(1), 53–53. Retrieved from https://dx.doi.org/10.1186/s12984-016-0162-5 10.1186/s12984-016-0162-5

Lu, R. R., Zheng, M. X., Li, J., Gao, T. H., Hua, X. Y., & Liu, G. (2020). Motor imagery based brain-computer interface control of continuous passive motion for wrist extension recovery in chronic stroke patients. *Neuroscience Letters*, *718*, 134727–134727.

Maier, M., Ballester, B. R., & Verschure, P. F. M. J. (2019). Principles of Neurorehabilitation After Stroke Based on Motor Learning and Brain Plasticity Mechanisms. *Frontiers in systems neuroscience*, *13*, 74–74.

Marquez-Chin, C., & Popovic, M. R. (2020). Functional electrical stimulation therapy for restoration of motor function after spinal cord injury and stroke: a review. *BioMedical Engineering OnLine*, *19*(1), 34–34. Retrieved from https://dx.doi.org/10.1186/s12938-020-00773-4 10.1186/s12938-020-00773-4

McConnell, A., Moioli, R., Brasil, F., Vallejo, M., Corne, D., Vargas, P., & Stokes, A. (2017). Robotic devices and brain-machine interfaces for hand rehabilitation post-stroke. *Journal of Rehabilitation Medicine*, *49*(6), 449–460. Retrieved from https://dx.doi.org/10.2340/16501977-2229 10.2340/16501977-2229

Mehrholz, J., Pohl, M., Platz, T., Kugler, J., & Elsner, B. (2015). Electromechanical and robot-assisted arm training for improving activities of daily living, arm function, and arm muscle strength after stroke. *Cochrane Database of Systematic Reviews*(11), 6876–6876. Retrieved from https://dx.doi.org/10.1002/14651858.cd006876.pub4

10.1002/14651858.cd006876.pub4

Moineau, B., Marquez-Chin, C., Alizadeh-Meghrazi, M., & Popovic, M. R. (2019). Garments for functional electrical stimulation: Design and proofs of concept. *Journal of Rehabilitation and Assistive Technologies Engineering*, *6*, 205566831985434–205566831985434. Retrieved from https://dx.doi.org/10.1177/2055668319854340 10.1177/2055668319854340

Mozaffarian, D., Benjamin, E. J., Go, A. S., Arnett, D. K., Blaha, M. J., & Cushman, M. (2016). Heart Disease and Stroke Statistics-2016 Update: A Report From the. *American Heart Association. Circulation*, *133*(4), 38–360.

Pereira, J., Sburlea, A. I., & Müller-Putz, G. R. (2018). EEG patterns of self-paced movement imaginations towards externally-cued and internally-selected targets. *Scientific Reports*, *8*(1), 13394–13394. Retrieved from https://dx.doi.org/10.1038/s41598-018-31673-2 10.1038/s41598-018-31673-2

Prange, G. B., Kottink, A. I. R., Buurke, J. H., Eckhardt, M. M. E. M., van Keulen-Rouweler, B. J., Ribbers, G. M., & Rietman, J. S. (2015). The Effect of Arm Support Combined With Rehabilitation Games on Upper-Extremity Function in Subacute Stroke. *Neurorehabilitation and Neural Repair*, *29*(2), 174–182. Retrieved from https://dx.doi.org/10.1177/1545968314535985 10.1177/1545968314535985

Ramos-Murguialday, A., Curado, M. R., Broetz, D., Yilmaz, Ö., Brasil, F. L., Liberati, G., Garcia-Cossio, E., Cho, W., Caria, A., Cohen, L. G., & Birbaumer, N. (2019). Brain-Machine Interface in Chronic Stroke: Randomized Trial Long-Term Follow-up. *Neurorehabilitation and Neural Repair*, *33*(3), 188–198. Retrieved from https://dx.doi.org/10.1177/1545968319827573 10.1177/1545968319827573

Remsik, A., Young, B., Vermilyea, R., Kiekhoefer, L., Abrams, J., Elmore, S. E., Schultz, P., Nair, V., Edwards, D., Williams, J., & Prabhakaran, V. (2016). *A review of the progression and future implications of brain-computer interface therapies for restoration of distal upper extremity motor function after stroke* (Vol. 13). Informa UK Limited. Retrieved from https://dx.doi.org/10.1080/17434440.2016.1174572 10.1080/17434440.2016.1174572

Rodgers, H., Bosomworth, H., Krebs, H. I., Wijck, F. V., Howel, D., & Wilson, N. (2019). Robot assisted training for the upper limb after stroke (RATULS): a multicentre randomised controlled trial. *The Lancet*, *394*, 51–62.

Ron-Angevin, R., Velasco-Álvarez, F., Álvaro Fernández-Rodríguez, Díaz-Estrella, A., Blanca-Mena, M. J., & Vizcaíno-Martín, F. J. (2017). Brain-Computer Interface application: auditory serial interface to control a two-class motor-imagery-based wheelchair. *Journal of NeuroEngineering and Rehabilitation*, *14*(1), 49–49. Retrieved from https://dx.doi.org/10.1186/s12984-017-0261-y 10.1186/s12984-017-0261-y

Rong, W., Tong, K. Y., Hu, X. L., & Ho, N. S. K. (2012). Combined Electromyography(EMG)-driven robotic system with Functional Electrical Stimulation (FES) for rehabilitation. In and others (Ed.), *38th Annual Northeast Bioengineering Conference (NEBEC)* (pp. 16–18).

Sale, P., Franceschini, M., Waldner, A., & Hesse, S. (2012). Use of the robot assisted gait therapy in rehabilitation of patients with stroke and spinal cord injury. *Eur J Phys Rehabil Med*, *48*(1), 111–121.

Simonetti, D., Zollo, L., Papaleo, E., Carpino, G., & Guglielmelli, E. (2016). Multimodal adaptive interfaces for 3D robot-mediated upper limb neuro-rehabilitation: An overview of bio-cooperative systems. *Robotics and Autonomous Systems*, *85*, 62–72. Retrieved from https://dx.doi.org/10.1016/j.robot.2016.08.012 10.1016/j.robot.2016.08.012

Soekadar, S. R., Birbaumer, N., Slutzky, M. W., & Cohen, L. G. (2015). Brain–machine interfaces in neurorehabilitation of stroke. *Neurobiology of Disease*, *83*, 172–179. Retrieved from https://dx.doi.org/10.1016/j.nbd.2014.11.025 10.1016/j.nbd.2014.11.025

Spüler, M., López-Larraz, E., & Ramos-Murguialday, A. (2018). On the design of EEG-based movement decoders for completely paralyzed stroke patients. *Journal of NeuroEngineering and Rehabilitation*, *15*(1), 110–110. Retrieved from https://dx.doi.org/10.1186/s12984-018-0438-z 10.1186/s12984-018-0438-z

Teo, W.-P., & Chew, E. (2014). Is Motor-Imagery Brain-Computer Interface Feasible in Stroke Rehabilitation? *PM&R*, *6*(8), 723–728. Retrieved from https://dx.doi.org/10.1016/j.pmrj.2014.01.006 10.1016/j.pmrj.2014.01.006

Veerbeek, J. M., Langbroek-Amersfoort, A. C., van Wegen, E. E. H., Meskers, C. G. M., & Kwakkel, G. (2017). Effects of Robot-Assisted Therapy for the Upper Limb After Stroke. *Neurorehabilitation and Neural Repair*, *31*(2), 107–121. Retrieved from https://dx.doi.org/10.1177/1545968316666957 10.1177/1545968316666957

Young, B. M., Nigogosyan, Z., Walton, L. M., Song, J., Nair, V. A., & Grogan, S. W. (2014). Changes in functional brain organization and behavioral correlations after rehabilitative therapy using a brain-computer interface. Front Neuroeng. *Changes in functional brain organization and behavioral correlations after rehabilitative therapy using a brain-computer interface. Front Neuroeng*, *7*, 26–26.

Yuan, H., & He, B. (2014). Brain-computer interfaces using sensorimotor rhythms: current state and future perspectives. *IEEE transactions on bio-medical engineering*(5), 1425–1435.

Yue, Z., Zhang, X., & Wang, J. (2017). Hand Rehabilitation Robotics on Poststroke Motor Recovery. *Behavioural Neurology*, 3908135–3908135.

Zhang, X., Yue, Z., & Wang, J. (2017). Robotics in Lower-Limb Rehabilitation after Stroke. *Behav Neurol*, 3731802–3731802.

Zhou, Z., Meng, W., Ai, Q., Liu, Q., & Wu, X. (2013). Practical Velocity Tracking Control of a Parallel Robot Based on Fuzzy Adaptive Algorithm. *Advances in Mechanical Engineering*, *5*, 574896–574896.