

Evaluation of the Effectiveness of Brain-Computer Interface in Post-Stroke Patient Rehabilitation

¹ALJA KOTRÍKOVÁ, PT; ¹ASSOC. PROF. DR. FRIDERIKA KRESAL

¹Institution of Higher Education for Physiotherapy FIZIOTERAPEVTIKA, Slovenska cesta 58, 1000 Ljubljana, Slovenia

Correspondence: tajnistvo@fizioterapevtika.si

ABSTRACT

The brain-computer interface has become a popular method for the rehabilitation and replacement of motor functions in patients after a stroke. The rehabilitation techniques enhance neuroplasticity by manipulating or self-regulating neurophysiological activity, while assistive technologies compensate for lost motor functions using robotic actuators or exoskeletons. The aim was to systematically review the scientific literature on the rehabilitation of stroke patients using brain-computer interface and to determine its therapeutic effectiveness in physiotherapy practice. The results obtained show that the most effective method of brain-computer interface rehabilitation is the use of brain-computer interface combined with motor imagery or movement intention tasks alongside functional electrical stimulation. Brain-computer interface therapy is considered safe, with evidence supporting its short-term therapeutic effect on the rehabilitation of upper limb motor function. **Keywords:** brain-computer interface, rehabilitation of stroke patients, physiotherapy, neurorehabilitation, neurotechnology

Ugotavljanje učinkovitosti možgansko-računalniškega vmesnika pri rehabilitaciji pacientov po možganski kapi

POVZETEK

Možgansko-računalniški vmesnik je postal priljubljena metoda za rehabilitacijo in nadomeščanje motoričnih funkcij pri pacientih po možganski kapi. Rehabilitacijske tehnike možgansko-računalniškega vmesnika omogočajo povečati nevroplastičnost z manipulacijo oziroma samoregulacijo nevrofiziološke aktivnosti, podporne tehnologije pa nadomeščajo izgubljene motorične funkcije s pomočjo robotskih aktuatorjev ali eksoskeletov. Namen je bil sistematično proučiti znanstveno literaturo o rehabilitaciji pacientov z možgansko-računalniškim vmesnikom po možganski kapi in ugotoviti terapevtsko učinkovitost možgansko-računalniškega vmesnika v fizioterapevtski praksi. Pridobljeni rezultati kažejo, da je kot najučinkovitejša metoda rehabilitacije z možgansko-računalniškim vmesnikom uporaba možgansko-računalniškega vmesnika z nalogo motorične predstave ali namere gibanja z funkcionalno električno stimulacijo. Terapija z možgansko-računalniškim vmesnikom velja za varno, z dokazi o njenem kratkoročnem terapevtskem učinku za rehabilitacijo motorične funkcije zgornje okončine. **Ključne besede:** možgansko-računalniški vmesnik, rehabilitacija pacientov po možganski kapi, fizioterapija, nevrorehabilitacija, nevrotehnologija

INTRODUCTION

A stroke is defined, according to the clinical criteria of the World Health Organization, as a “rapidly developing clinical sign (usually focal) of disturbance of cerebral function lasting more than 24 hours or leading to death” (1). Today, it remains one of the leading causes of disability, with many patients suffering from irreversible cognitive or physical impairments (2). At the beginning of the 21st century, the age-standardized incidence of stroke in Europe ranged from 95 to 290 per 100,000 individuals per year (3), with a prevalence rate between 5% and 10% among older adults (3). In high-income countries, stroke affects approximately one in five individuals, whereas in low-income countries it affects nearly one in two (4).

At the most basic level, strokes are divided into hemorrhagic and ischemic types. Hemorrhagic strokes can be either intraparenchymal or subarachnoid, while ischemic strokes are further categorized as cardioembolic, atherosclerotic, lacunar, those due to other specific causes (such as dissection, vasculitis, or genetic disorders), and those of unknown cause. The risk factors for both hemorrhagic and ischemic strokes are largely similar and include hypertension, hyperlipidemia, heart disease, diabetes mellitus, unhealthy diet, physical inactivity, smoking, alcohol consumption, stress, and depression (5).

The primary objective of stroke treatment is to restore cerebral blood flow and address resulting neurological damage (6). Common rehabilitation approaches include mirror therapy, early mobilization, the Bobath or Carr and Shepherd approaches, gait training with support, functional electrical stimulation (FES), virtual reality training, and kinesiotherapy (7).

Patients recovering from stroke frequently experience substantial limitations in performing activities of daily living. Consequently, the restoration of motor function in paretic limbs is one of the primary goals of physiotherapeutic rehabilitation. Rehabilitation using neurotechnology and robotics has the potential to enhance brain neuroplasticity by promoting interaction between proprioceptive and other sensory inputs with motor outputs, thereby facilitating changes in the functional connectivity of frontoparietal networks associated with motor planning and execution (8).

Brain–computer interfaces (BCIs) play a crucial role in the rehabilitation of motor disorders resulting from stroke. In BCI-based therapy, a neurofeedback loop is established that enables patients to modulate and control their own brain activity. Through neurofeedback, patients learn to self-regulate electroencephalographic (EEG) activity, which induces brain activation through motor imagery (MI) or the intention to move (2). Motor imagery refers to the mental representation of a movement, aiming to activate the same neural regions responsible for voluntary motor control (9). During rehabilitation involving BCIs, motor imagery activates neural circuits associated with actual movement execution, allowing functional reorganization of neurons through neuroplasticity (10).

BCIs can be categorized as invasive or non-invasive, with non-invasive EEG-based BCIs being the most widely used in neurorehabilitation. Additionally, BCIs are often divided into assistive and rehabilitative systems (2). Rehabilitative BCIs promote neuroplasticity by manipulating or self-regulating neurophysiological activity, whereas assistive BCIs aim to restore lost motor functions by means of robotic actuators or functional electrical stimulation (FES). The primary goal of BCI-assisted rehabilitation is to promote reorganization of the damaged hemisphere by modulating activity in the ipsilesional sensorimotor cortex (11). The most frequently used BCIs in stroke rehabilitation are based on non-invasive EEG combined with visual feedback or a combination of visual and kinesthetic/proprioceptive feedback (12).

Despite the growing evidence of their potential, one of the main challenges in using BCIs in rehabilitation is the lack of large-scale, high-quality research that thoroughly defines the most effective intervention parameters and reliably confirms their efficacy within physiotherapy practice.

METHODS

This scientific article is based on a systematic review of the literature, conducted using the PubMed and PEDro databases. The literature search was performed in October 2024. The following keywords were used in both Slovenian and English: brain–computer interface and stroke. The inclusion criteria were as follows: (a) Articles written in English; (b) Studies published within the last 10 years; (c)

High-quality studies, including scientific articles, systematic reviews, meta-analyses, and randomized controlled clinical trials (RCTs); (e) Clinical studies that included a control group; (f) Studies with a sample size of $n > 40$ participants.

The methodological quality of the selected studies was evaluated using the PEDro scale. The exclusion criteria included duplicate records, as well as studies that were methodologically or content-wise inadequate for the purpose of this review. The PEDro scale is a widely used tool for assessing the methodological quality of clinical trials. It is based on 11 criteria: (a) Specification of eligibility criteria, (b) Random allocation of participants, (c) Concealed allocation, (d) Baseline comparability of groups, (e) Blinding of participants, (f) Blinding of therapists, (g) Blinding of assessors, (h) Adequate follow-up, (i) Intention-to-treat analysis, (j) Statistical comparison between groups for at least one key outcome, and (k) Reporting of point estimates and measures of variability. The total PEDro score ranges from 0 to 10 (the first item is not included in the score) and reflects the number of criteria met in a clinical trial. A score between 6 and 10 indicates high methodological quality, 4 to 5 denotes moderate quality, and a score of ≤ 3 reflects low quality (13). All studies meeting the inclusion criteria were assessed using this scale to ensure consistency and reliability in the quality evaluation process.

RESULTS

The literature search using the specified keywords and phrases yielded a total of 62 results in the PubMed database and 19 results in the PEDro database. In PubMed, the keywords brain–computer interface and stroke produced 62 results. The search was limited to articles published in English within the last 10 years. Further filters were applied to include only studies of appropriate type and quality—namely, systematic reviews, meta-analyses, and randomized controlled clinical trials (RCTs)—that also included a control group and a participant sample size greater than 40 ($n > 40$). Based on the titles and abstracts, 50 studies were initially selected from both databases for detailed review. In the PEDro database, the keyword brain–computer interface yielded 19 results. After reviewing the titles and abstracts, 10 studies were selected for further analysis. Following the review of all 60 selected studies, and after applying the exclusion criteria (removal of duplicates and methodologically or contextually inadequate papers), a total of 18 studies were ultimately included in the final analysis. These studies were deemed the most suitable according to the pre-defined content-related and quality criteria established in the Methods section.

DISCUSSION

Stroke remains one of the leading causes of disability and death among older adults, and patients who have suffered a stroke often experience severe impairment of motor function in paretic limbs. Brain–computer interfaces (BCIs) are increasingly being used in stroke rehabilitation, and growing evidence suggests that they may facilitate the restoration of upper limb motor function.

Shou, Wang, and Yang (2023) investigated the effects of rehabilitation using real BCIs compared to sham BCIs on the recovery of upper limb motor function after stroke. Their systematic review analyzed randomized controlled trials (RCTs) comparing real versus sham BCI rehabilitation in post-stroke patients, including only high-quality RCTs and excluding quasi-randomized trials. A total of 11 studies with 334 participants aged 14–74 years were reviewed. Methodological quality was assessed using the Cochrane Risk of Bias tool. All included studies reported random sequence generation, incomplete outcome data, and selective reporting. Four studies described allocation concealment, and five reported participant and staff blinding. All but two studies reported blinding of outcome assessors. According to the results, BCI rehabilitation may improve upper limb motor function after stroke. However, the authors emphasized several limitations, including the small number of studies, limited sample sizes, and potential publication bias, all of which may have influenced the overall conclusions (14).

In a meta-analysis by Nojima et al. (2021), 16 studies comprising a total of 382 participants were included—15 RCTs and one non-randomized controlled study. Eleven studies involved patients with chronic stroke, while five included subacute patients. BCI rehabilitation programs lasted from 2 to 8

weeks, with weekly therapy durations ranging from 40 to 200 minutes, administered 2–5 times per week. Therapy sessions typically included 30–60 minutes of conventional physiotherapy supplemented by BCI-assisted robotic or non-invasive BCI training. The control groups received equivalent durations of conventional therapy combined with sham robotic or BCI therapy. Motor outcomes were primarily assessed using the Fugl-Meyer Assessment (FMA), Action Research Arm Test (ARAT), Modified Ashworth Scale, and Motor Activity Log. The meta-analysis revealed that real BCI rehabilitation produced moderate positive effects on motor function of paretic limbs compared with sham BCI. Overall, BCI rehabilitation appeared more effective than conventional interventions in post-stroke patients; however, high heterogeneity and potential bias among studies limited the conclusiveness of the findings (11).

Bai et al. (2020) conducted a systematic review and meta-analysis to evaluate the effects of BCI interventions on upper limb functional recovery after stroke and to examine the influence of transcranial direct current stimulation (tDCS) on BCI-based rehabilitation. Their review included 18 single-group studies and 15 controlled studies, of which 13 were RCTs. The experimental groups included 174 participants and the control groups 139 participants. Alongside conventional physiotherapy, interventions included BCI orthoses, robotic devices, exoskeletons, and BCI-FES systems. Various neurofeedback paradigms were used, such as motor imagery (MI), active observation, and movement intention tasks. Intervention durations ranged from 2 to 6 weeks, with 3–5 sessions per week lasting 20–90 minutes. The mean PEDro score was 6.6 ± 1.7 . Pooled results demonstrated that BCI significantly improved upper limb motor function compared with control interventions (15).

Kancheva et al. (2023) analyzed evidence on the relationship between stroke lesion location and sensorimotor rhythm (SMR). Due to high variability in lesion localization, frequency band definitions, and outcome metrics across studies, a meta-analysis was not feasible. Their systematic review synthesized data from 12 studies with 317 participants (161 experimental, 156 control). Of these, 62 were in the acute phase, 61 subacute, and 38 chronic. The majority had ischemic strokes (145 patients), while only 2 had hemorrhagic strokes and 14 were unspecified. Lesion locations varied—49 cortical, 71 subcortical, 22 mixed (cortico-subcortical), 4 infratentorial, and 15 pontine. Neurofeedback paradigms included resting state, movement intention, motor execution, and MI. Patients performing motor tasks with their paretic hands showed reduced alpha and beta (15–25 Hz) event-related desynchronization (ERD) compared with controls. Cortical lesions produced stronger alpha and beta ERD reductions in the ipsilesional hemisphere, whereas subcortical strokes affected bilateral ERD and event-related synchronization (ERS). The review partially supported the hypothesis that SMR patterns differ according to lesion location, with cortical lesions associated with more pronounced SMR alterations. SMR recovery over time correlated with motor improvement, suggesting that early ipsilesional ERD power and lateralization predict better motor outcomes. Methodological limitations included inconsistent lesion localization, incomplete baseline data, and small sample sizes, although five studies were rated as high quality and seven as moderate (16).

Mansour et al. (2021) performed a systematic review and meta-analysis of 12 RCTs with 298 participants. Overall, BCI interventions were significantly more effective than control interventions immediately after therapy. In 9 of the 12 studies, the BCI group achieved higher upper limb FMA scores than the control group. In 8 studies, participants were in the chronic stage (>6 months post-stroke), and in 4 studies, in the subacute stage (1–6 months). The overall motor recovery effect favored BCIs in both groups, with larger effects observed in subacute patients. Among neurofeedback paradigms, both MI and movement intention were used, with movement intention producing greater motor recovery. Feedback modalities included FES, robotic hands and exoskeletons, haptic buttons, soft robotic gloves, visual feedback, and virtual hands. The most significant improvement in upper limb motor recovery was achieved in studies using FES as feedback. The meta-analysis concluded that BCIs produced both short- and long-term gains in upper limb function, supporting the use of movement intention combined with FES as an optimal neurofeedback paradigm. None of the included studies were rated as low quality according to the PEDro scale (13).

Liu et al. (2023) conducted an RCT investigating the effects of BCI-based motor imagery (MI)

rehabilitation on upper limb motor function and attention in hemiplegic post-stroke patients. Sixty participants were randomized equally into a control group (CG) and experimental group (EG). The CG received conventional rehabilitation—including motor, occupational, and physical therapy, coordination training, antispastic treatment, acupuncture, and moxibustion—while the EG received the same program plus 20-minute BCI-MI sessions five times weekly for three weeks. Only patients with sufficient MI ability (Kinesthetic and Visual Imagery Questionnaire score ≥ 55) were included. The control group received an additional 20 minutes of FES as part of their standard therapy. The study was single-blinded, with blinded outcome assessment. After three weeks, the BCI-MI group demonstrated significantly greater improvements in both motor function and attention than the control group, supporting the integration of MI-based BCIs in post-stroke rehabilitation (17).

Ma et al. (2024) examined the effects of BCI-MI rehabilitation on upper limb motor recovery in chronic hemiplegic patients. Forty participants were randomized into BCI and control groups. Both groups received standard physiotherapy and occupational therapy for two weeks, focusing on muscle tone control, limb coordination, balance, and daily activities. The BCI group additionally underwent ten 40-minute BCI-MI sessions. This group showed significantly greater improvement in upper limb motor function, with distinct activation and inhibition patterns observed in multiple brain regions. The study concluded that BCI therapy is an effective and safe intervention for upper limb rehabilitation following stroke (18).

Peng et al. (2022) conducted an updated meta-analysis of 16 studies with 488 participants, examining the efficacy and safety of BCI in post-stroke upper limb rehabilitation. All studies reported a positive effect of BCI on upper limb motor recovery. Although no significant differences were found between BCI and control groups in ARAT results, BCI participants showed improved cortical activation associated with motor recovery. Most interventions lasted four weeks, and the largest improvements in FMA scores occurred during or after this period. Additionally, results from the Modified Barthel Index (MBI) in seven studies indicated enhanced independence and quality of life. However, lack of detailed data such as lesion location was noted as a key limitation (19).

Yang et al. (2022) conducted a meta-analysis of 13 studies (258 participants) following PRISMA guidelines to evaluate BCI effectiveness in upper limb motor rehabilitation. One study was rated Grade A and 12 as Grade B due to issues such as selective reporting and limited blinding. The primary outcome measure was the Fugl-Meyer Assessment (FMA), supported by the Modified Ashworth Scale and MBI. Results showed that BCI rehabilitation significantly improved upper limb motor function in post-stroke patients (20).

Kruse et al. (2020) performed a systematic review and meta-analysis including 14 studies with 362 participants after ischemic or hemorrhagic stroke. The mean participant age was 53 ± 5.8 years, and the average time since stroke onset was 15.7 ± 18.2 months. Interventions lasted 3 days to 6 weeks, with 2–3 sessions weekly. The main outcome measure was the upper limb FMA. The analysis revealed that combining BCI rehabilitation with conventional therapy improved motor and brain function recovery. Risk of bias was generally low. The authors emphasized the importance of standardized MI assessment and suggested incorporating neuropsychological measures (attention, concentration) into evaluations (9).

Monge-Pereira et al. (2017) systematically reviewed EEG-based BCI interventions for upper limb rehabilitation post-stroke, including 13 studies (4 RCTs, 1 controlled study, 4 case series, and 4 case reports) involving 141 patients. Methodological quality scores ranged from 6 to 15. BCIs included movement execution, MI, visual or haptic feedback, robotic assistance, and mechanical orthoses. Five studies combined conventional physiotherapy with BCI. Several studies demonstrated immediate and follow-up improvements in FMA and ARAT scores, particularly among subacute and chronic patients. However, differences between control and experimental groups were often not statistically significant (21).

Xie et al. (2022) conducted a meta-analysis of 17 studies (410 participants) assessing BCI effectiveness and safety for post-stroke upper limb rehabilitation. All studies used the FMA. Subgroup analyses showed that BCI interventions produced greater improvements in chronic and subacute patients compared to controls. BCI combined with FES or visual feedback was more effective than BCI-robot

interfaces alone. Three studies (80 participants) evaluated ADL outcomes using the MBI, with two showing clinically meaningful improvements. BCI-based rehabilitation demonstrated greater standardized mean differences compared with mirror therapy, constraint-induced movement therapy, and MI, and similar or superior results compared with robotic and virtual reality-based therapies. However, some participants reported fatigue after 20–30 minutes of training (22).

Carvalho, Dias, and Cerqueira (2019) reviewed advances in BCI technologies for restoring upper limb motor function. Their review included nine high-quality studies with 233 participants aged 49–67 years, with time since stroke ranging from 1.7 to 71 months. Various types of sensory feedback were used, including robotic arms, orthoses, and FES. Seven studies combined BCI therapy with conventional rehabilitation methods such as exercise, occupational and physical therapy, and kinesiotherapy. The authors concluded that neurofeedback-based BCIs, especially when combined with robotic or FES assistance, can significantly improve motor function; however, long-term neurophysiological outcomes remain insufficiently understood (12).

Fu, Chen, and Jia (2022) analyzed 15 RCTs examining mental tasks in BCIs based on sensorimotor rhythm (SMR). Movement intention tasks appeared more effective than MI alone, suggesting they may be better suited for stroke patients. Combining proprioceptive feedback (via exoskeletons, orthoses, robots, or FES) with visual feedback may create a more enriched rehabilitation environment. The authors noted that BCI therapy enhances ipsilesional sensorimotor cortex activity, increasing cortical excitability and EEG modulation (ERD), with stronger SMR control predicting better motor outcomes (23).

Ren et al. (2024) conducted a meta-analysis evaluating BCI-FES rehabilitation in 290 chronic and subacute patients across ten RCTs. BCI thresholds were either adaptive or fixed, and mental tasks included MI, action observation, or movement intention. Therapy durations ranged from 20–60 minutes per session (4–24 total hours). The average PEDro score was 7. Results showed that BCI-FES significantly improved upper limb function compared with controls, with no significant difference between adaptive and fixed thresholds (24).

Khan et al. (2023) reviewed 25 studies on FES systems for upper limb neurorehabilitation. Systems were categorized as open-loop (manually controlled) or closed-loop (BCI- or EMG-controlled). FES-based systems produced significant improvements in upper limb recovery, with BCI-FES and EMG-FES yielding the largest FMA and ARAT gains. Closed-loop systems were more effective than open-loop ones. The RecoveriX system by g.tec was identified as the only commercially available BCI-FES platform, though it remains in early clinical adoption. Limitations included small sample sizes, lack of control groups, and motivational challenges due to lengthy and repetitive sessions (10).

Baniqued et al. (2021) reviewed 30 studies on BCI-hand robotic systems for fine motor rehabilitation. Eleven clinical studies included 208 stroke patients. Two RCTs compared BCI interventions with conventional hand therapy or sham feedback, while several others assessed classification accuracy and clinical improvements. Outcome measures included the FMA, ARAT, and grip strength. Only two studies achieved a PEDro score of 7. The review confirmed that BCI-robot systems show promising results but highlighted a need for more rigorous, standardized clinical trials (25).

Frolov et al. (2017) conducted a multicenter RCT comparing active BCI-controlled hand exoskeleton training with passive, non-BCI-guided exoskeleton movement in 74 stroke patients (55 ischemic, 19 hemorrhagic). The BCI group demonstrated significantly greater improvements in grasping and gross motor movements than controls. Both subacute and chronic patients benefited, though the study was limited by small group sizes, unequal randomization, and lack of long-term follow-up (26).

Most current studies focus on non-invasive BCI applications, primarily EEG-based, due to accessibility and simplicity, although some employ MEG or NIRS. Neurofeedback paradigms typically include MI, movement intention, and active observation, but consensus on the most effective approach has yet to be reached. Feedback types such as FES, robotic orthoses, and exoskeletons have all shown benefits, with FES demonstrating the greatest efficacy, particularly in patients lacking voluntary movement. In contrast, robotic and exoskeletal systems appear more suitable for patients retaining partial active movement.

All selected studies investigated upper limb rehabilitation. Few small-scale studies examined lower

limb function or gait, which were not included in this review. Future research should therefore emphasize lower limb BCI rehabilitation.

To establish the efficacy of BCIs in stroke rehabilitation, long-term, large-sample, double-blind RCTs using objective neuroimaging measures are essential. Study protocols should standardize BCI parameters—such as neurofeedback type, signal acquisition method, signal processing technique, and classification algorithms—to minimize bias and enhance reproducibility. Comparative trials assessing different parameter combinations alongside conventional physiotherapy outcomes are needed.

Based on the available literature, the most promising configuration for BCI-EEG rehabilitation involves motor imagery or movement intention tasks combined with FES feedback, which appears to produce the most consistent improvements in post-stroke motor recovery.

CONCLUSIONS

Current evidence indicates that BCI-based rehabilitation produces significant short-term improvements in upper limb motor function after stroke; however, findings regarding long-term effects remain inconsistent. Most existing studies focus primarily on upper limb rehabilitation, while the application of BCIs for lower limb recovery remains largely unexplored.

Based on the systematically reviewed evidence, BCI rehabilitation demonstrates substantial therapeutic potential for improving upper limb motor function in post-stroke patients. Future research should focus not only on statistically significant differences but also on clinically meaningful outcomes—specifically, how rehabilitation impacts a patient's ability to perform activities of daily living and overall quality of life.

According to the analyzed literature, the most effective approach for post-stroke BCI rehabilitation appears to be the use of an EEG-based BCI system employing motor imagery (MI) or movement intention tasks in combination with functional electrical stimulation (FES) feedback.

It is advisable to incorporate short breaks of approximately 15 minutes during one-hour sessions to help patients maintain concentration. Based on current findings, BCI therapy should be conducted 2–3 times per week and initiated at least six months after stroke onset, when spontaneous neurological recovery has typically plateaued.

For clearer and more reliable therapeutic outcomes, future studies should adopt standardized training parameters, larger participant samples, and long-term follow-up using objective neurophysiological and neuroimaging measures. Such research will be essential for confirming the sustained clinical and neuroplastic benefits of BCI-assisted rehabilitation in stroke recovery.

LITERATURE

1. Aho, K., Harmsen, P., Hatano, S., Marquardsen, J., Smirnov, V. E., & Strasser, T. (1980). Cerebrovascular disease in the community: results of a WHO collaborative study. *Bulletin of the World Health Organization*, 58(1), 113–130.
2. Penev Y.P, Beneke A., Root K.T., Meisel E., Kwak S., Diaz M.J., Root J.L., Hosseini M.R., Lucke-Wold B. (2023). Therapeutic Effectiveness of Brain Computer Interfaces in Stroke Patients: A Systematic Review. *Journal of Exp Neurol.*, 4(3).
3. Béjot, Y., Bailly, H., Durier, J., & Giroud, M. (2016). Epidemiology of stroke in Europe and trends for the 21st century. *Presse medicale (Paris, France: 1983)*, 45(12 Pt 2), e391–e398.
4. Hilkens, N. A., Casolla, B., Leung, T. W., & de Leeuw, F. E. (2024). Stroke. *Lancet (London, England)*, 403(10446), 2820–2836.
5. Boehme, A. K., Esenwa, C., & Elkind, M. S. (2017). Stroke Risk Factors, Genetics, and Prevention. *Circulation research*, 120(3), 472–495.
6. Kuriakose, D., & Xiao, Z. (2020). Pathophysiology and Treatment of Stroke: Present Status and Future Perspectives. *International journal of molecular sciences*, 21(20), 7609.
7. Roesner, K., Scheffler, B., Kaehler, M., Schmidt-Maciejewski, B., Boettger, T., & Saal, S. (2024). Effects of physical therapy modalities for motor function, functional recovery, and post-stroke complications in patients with severe stroke: a systematic review update. *Systematic Reviews*,

- 13(1), 270.
8. Bressi, F., Bravi, M., Campagnola, B., Bruno, D., Marzolla, A., Santacaterina, F., ... & Sterzi, S. (2020). Robotic treatment of the upper limb in chronic stroke and cerebral neuroplasticity: A systematic review. *Journal of Biological Regulators & Homeostatic Agents*, 34(5 Suppl. 3), 11-44.
 9. Kruse, A., Suica, Z., Taeymans, J., & Schuster-Amft, C. (2020). Effect of brain-computer interface training based on non-invasive electroencephalography using motor imagery on functional recovery after stroke-a systematic review and meta-analysis. *BMC neurology*, 20(1), 1-14.
 10. Khan, M. A., Fares, H., Brunner, I. C., Lansberg, M., Poon, A., & Meador, K. J. (2023). A systematic review on functional electrical stimulation-based rehabilitation systems for upper limb post-stroke recovery. *Frontiers in Neurology*, 14, 1272992.
 11. Nojima, I., Sugata, H., Takeuchi, H., Mima, T. (2021). Brain-computer interface training based on brain activity can induce motor recovery in patients with stroke: A meta-analysis. *Sage Journals*, 36(2).
 12. Carvalho, R., Dias, N., & Cerqueira, J. J. (2019). Brain-machine interface of upper limb recovery in stroke patient's rehabilitation: a systematic review. *Physiotherapy Research International*, 24(2), e1764.
 13. Mansour, S., Ang, K.K., Nair, K.P.S., Phua, K.S., Arvaneh, M. (2021). Efficacy of brain-computer interface and the impact of its design characteristics on poststroke upper-limb rehabilitation: a systematic review and metaanalysis of randomized controlled trials. *Sage Journals*, 53(1).
 14. Shou, YZ., Wang, XH., Yang, GF. (2023). Verum versus sham brain-computer interface on upper limb function recovery after stroke: A systematic review and meta-analysis of randomized controlled trials. *Medicine (Baltimore)*, 102(26).
 15. Bai, Z., Fong, K.N.K., Zhang, J.J., Chan, J., Ting, K.H. (2020). Immediate and long-term effects of BCI-based rehabilitation of the upper extremity after stroke: a systematic review and meta-analysis. *Journal of NeuroEngineering and Rehabilitation*, 17(57).
 16. Kancheva, I., van der Salm, S. M. A., Ramsey, N. F., & Vansteensel, M. J. (2023). Association between lesion location and sensorimotor rhythms in stroke - a systematic review with narrative synthesis. *Neurological sciences: official journal of the Italian Neurological Society and of the Italian Society of Clinical Neurophysiology*, 44(12), 4263–4289.
 17. Liu, X., Zhang, W., Li, W., Zhang, S., Lv, P., & Yin, Y. (2023). Effects of motor imagery-based brain-computer interface on upper limb function and attention in stroke patients with hemiplegia: a randomized controlled trial. *BMC neurology*, 23(1), 136.
 18. Ma, Z. Z., Wu, J. J., Cao, Z., Hua, X. Y., Zheng, M. X., Xing, X. X., Ma, J., & Xu, J. G. (2024). Motor imagery-based brain-computer interface rehabilitation programs enhance upper extremity performance and cortical activation in stroke patients. *Journal of neuroengineering and rehabilitation*, 21(1), 91.
 19. Peng, Y., Wang, J., Liu, Z., Zhong, L., Wen, X., Wang, P., Gong, X., & Liu, H. (2022). The Application of Brain-Computer Interface in Upper Limb Dysfunction After Stroke: A Systematic Review and Meta-Analysis of Randomized Controlled Trials. *Frontiers in human neuroscience*, 16, 798883.
 20. Yang, W., Zhang, X., Li, Z., Zhang, Q., Xue, C., & Huai, Y. (2022). The Effect of Brain-Computer Interface Training on Rehabilitation of Upper Limb Dysfunction After Stroke: A Meta-Analysis of Randomized Controlled Trials. *Frontiers in neuroscience*, 15, 766879.
 21. Monge-Pereira, E., Ibañez-Pereda, J., Alguacil-Diego, I. M., Serrano, J. I., Spottorno-Rubio, M. P., & Molina-Rueda, F. (2017). Use of electroencephalography brain-computer interface systems as a rehabilitative approach for upper limb function after a stroke: a systematic review. *PM&R*, 9(9), 918-932.
 22. Xie, Y. L., Yang, Y. X., Jiang, H., Duan, X. Y., Gu, L. J., Qing, W., Zhang, B., & Wang, Y. X. (2022). Brain-machine interface-based training for improving upper extremity function after stroke: A meta-analysis of randomized controlled trials. *Frontiers in neuroscience*, 16, 949575.
 23. Fu, J., Chen, S., & Jia, J. (2022). Sensorimotor Rhythm-Based Brain-Computer Interfaces for Motor Tasks Used in Hand Upper Extremity Rehabilitation after Stroke: A Systematic Review. *Brain Sciences*, 13(1), 56.

24. Ren, C., Li, X., Gao, Q., Pan, M., Wang, J., Yang, F., Duan, Z., Guo, P., & Zhang, Y. (2024). The effect of brain-computer interface controlled functional electrical stimulation training on rehabilitation of upper limb after stroke: a systematic review and meta-analysis. *Frontiers in human neuroscience*, 18, 1438095.
25. Baniqued, P. D. E., Stanyer, E. C., Awais, M., Alazmani, A., Jackson, A. E., Mon-Williams, M. A., ... & Holt, R. J. (2021). Brain-computer interface robotics for hand rehabilitation after stroke: A systematic review. *Journal of neuroengineering and rehabilitation*, 18(1), 1-25.
26. Frolov, A. A., Mokienko, O., Lyukmanov, R., Biryukova, E., Kotov, S., Turbina, L., Nadareyshvily, G., & Bushkova, Y. (2017). Post-stroke Rehabilitation Training with a Motor-Imagery-Based Brain-Computer Interface (BCI)-Controlled Hand Exoskeleton: A Randomized Controlled Multicenter Trial. *Frontiers in neuroscience*, 11, 400.