 10.3217/978-3-99161-093-9-015

A Feasibility Study of a Motor Imagery–Based Brain–Computer Interface for Post-Stroke Patients

V. Martínez-Cagigal[1,2,3], S. Moreno-Calderón[1,3], A. Cisnal[4], S. Pérez-Velasco[1,2], A. Martín-Fernández[1,2,3], E. Santamaría-Vázquez[1,2,3], J. C. Fraile[4], J. Pérez-Turiel[4], R. Hornero[1,2,3]

[1] Biomedical Engineering Group (GIB), University of Valladolid, Valladolid, Spain
[2] Network Biomedical Research Center for Bioengineering, Biomaterials and Nanomedicine (CIBER-BBN), VAlladolid, Spain
[3] Valladolid Health Research Institute (IBioVALL), Valladolid, Spain
[4] Institute of Advanced Production Technologies (ITAP), University of Valladolid, Valladolid, Spain

E-mail: victor.martinez.cagigal@uva.es

ABSTRACT: Stroke is a major contributor to chronic disability, and many survivors continue to experience pronounced upper-limb weakness despite standard rehabilitation. By converting motor intent into real-time sensory feedback, brain–computer interfaces (BCIs) could help re-engage the sensorimotor loop. However, findings across clinical studies remain mixed, especially for robot-assisted approaches. In this feasibility study, we investigated whether a noninvasive motor-imagery (MI) BCI providing concurrent multimodal feedback (visual avatar and robot-assisted hand motion) yields additional improvements beyond usual care. Sixteen patients with a first-ever stroke were assigned to conventional therapy alone (CG, $n = 6$) or to the same therapy supplemented with 23 one-hour BCI sessions (EG, $n = 10$). Online EEG from eight sensorimotor channels was used to classify left- versus right-hand kinesthetic MI, and motor, cognitive, and functional tests were evaluated before and after the intervention. The EG showed significant within-group gains in voluntary motor control and coordination of the affected hand, episodic memory and visuoconstructive ability, as well as functional measures such as perceived general health and independence. These preliminary findings suggest that BCI-based therapies may enhance post-stroke rehabilitation.

INTRODUCTION

Stroke remains one of the most pressing public health challenges worldwide, ranking as the second leading cause of death and a leading cause of long-term disability [1]. Its incidence and prevalence continue to rise, particularly in Europe, where stroke represents the primary cause of acquired disability. Clinical outcomes vary according to lesion characteristics, but a substantial proportion of survivors experience persistent motor and cognitive impairments that compromise activities of daily living. Upper-limb paresis is especially prevalent, affecting up to 80% of patients in the acute stage and persisting in a significant fraction beyond six months [2]. Although interventions such as constraint-induced movement therapy, conventional physiotherapy, mirror therapy, and robot-assisted rehabilitation are routinely implemented, their effectiveness remains limited [3]. In this context, BCIs have emerged as a promising therapeutic strategy. By decoding movement intention from neural activity, typically via electroencephalography (EEG), and coupling it with contingent sensory feedback, BCI systems establish a closed sensorimotor loop that could facilitate functional recovery [2].

Over the past decade, multiple randomized controlled trials (RCTs) have evaluated BCI-based interventions for post-stroke rehabilitation [4, 5]. Collectively, these studies report that BCI-assisted therapy yields greater improvements in upper-limb motor function, commonly assessed with the Fugl–Meyer Assessment–Upper Extremity (FMA-UE), than conventional therapy alone [4, 5]. Functional electrical stimulation (FES)-based BCIs appear to produce the largest effect sizes, while robotic-assisted BCIs demonstrate significant motor gains but do not consistently outperform robotic therapy delivered without neural control [4]. Treatment effects tend to be more pronounced in subacute patients than in chronic populations, underscoring the importance of early intervention. Although motor imagery (MI) remains the most widely implemented paradigm, action observation has also shown promising, and in some cases superior, outcomes. Meta-analytic evidence further suggests that optimal protocols typically involve sessions lasting 20–90 minutes, administered several times per week over approximately three to four weeks, and that improvements may reflect genuine neuroplastic changes rather than just compensatory mechanisms [4, 5].

Despite these encouraging findings, important methodological limitations persist. Meta-analyses consistently highlight substantial heterogeneity across studies in terms of patient characteristics, time since stroke onset, feedback modalities, signal processing approaches, number of sessions, and pre-post measures. Sample sizes are frequently small, limiting statistical power and precluding

10.3217/978-3-99161-093-9-015

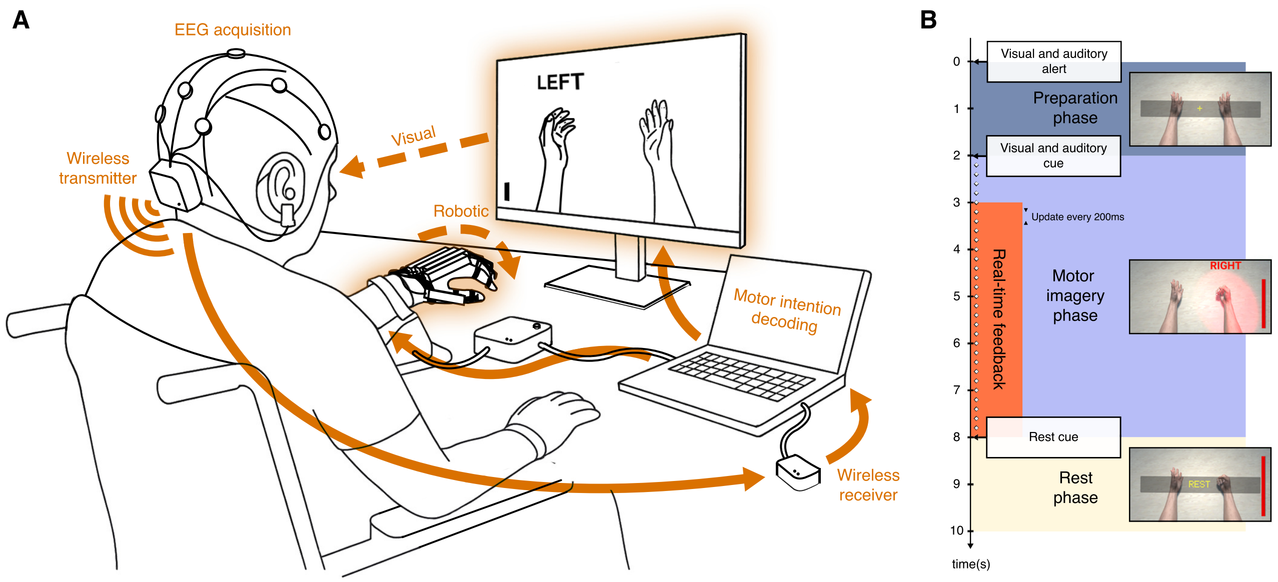

Figure 1: (A) General overview of the BCI system. EEG signals are acquired using portable hardware and transmitted wirelessly in real-time to a laptop, where the user's motor intentions are decoded. The system delivers multimodal feedback (dashed lines) comprising (1) visual feedback in the form of an avatar hand movement and (2) concurrent robotic assistance for flexion or extension movements applied to the paretic hand. (B) The structure of a MI trial, composed of (1) a preparation phase of 2 s, (2) a MI phase of 6 s (initiated by cue presentation and followed by continuous decoding of epochs every 200 ms), and (3) a rest phase of 2 s.

robust subgroup analyses [4, 5]. Thus, further studies are required to clarify the clinical value of specific BCI configurations and training paradigms. The present study addresses these gaps by evaluating a novel MI–based BCI system that delivers simultaneous multimodal feedback (embodied visual avatars with robotic-assisted movement) for stroke patients. By assessing motor, cognitive, and functional outcomes following a structured intervention protocol, this work seeks to provide more evidence regarding the therapeutic potential of MI-based BCI rehabilitation after stroke.

MATERIALS AND METHODS

Sixteen patients (mean age 66.63±11.42 years; 8 females) with first-ever stroke and upper-limb hemiparesis were recruited from the Benito Menni Hospital Center (Valladolid, Spain) after providing written informed consent. Demographic data are shown in Table 1. The majority were in the early subacute phase (7 days to 3 months post-stroke, $n = 13$), with two in the late subacute phase and one in the chronic stage; both ischemic ($n = 11$) and hemorrhagic ($n = 5$) etiologies were represented, with heterogeneous lesion locations and variable laterality of impairment. The study was approved by the local ethics committee (reference: CASVE-NM-22-617) and conducted in accordance with the Declaration of Helsinki, with all data anonymized prior to analysis. Inclusion criteria comprised age ≥30 years, neuroimaging-confirmed first-ever stroke, and at least 7 days post-onset, whereas exclusion criteria included severe cognitive or behavioral disturbances, impaired consciousness, high seizure risk, major visual deficits, severe spasticity, intense pain during mobilization, and other medical or dermatological conditions interfering with participation.

The overall system and trial structure are illustrated in Figure 1. A monitor positioned in front of the participant, who was seated at a table with both upper limbs supported, presented a cue-based MI paradigm, while the paretic hand was secured to a robotic exoskeleton mounted on an inclined support to ensure anatomical alignment and mechanical stability. During each trial, randomized visual cues instructed the participant to perform kinesthetic imagery of left- or right-hand movements during trials of 6 s. The system decoded participants' motor intentions in real-time and translated them into contingent multimodal feedback: the inferred movement was rendered by virtual avatar hands and, when the paretic hand was targeted, the robotic device delivered assisted wrist and finger flexion. This closed-loop setup therefore linked motor intention with congruent visual and proprioceptive feedback.

EEG data were acquired using a wireless system (g.Nautilus PRO, g.Tec, Austria) with active electrodes positioned over the sensorimotor cortex (FC5, FC6, C1, C2, C3, C4, CP5, and CP6; referenced to the earlobe and grounded at AFz). Signal acquisition, online processing, and feedback visualization were implemented in MEDUSA© v2023 (medusabci.com) [6]. The processing pipeline included band-pass filtering (8–30 Hz), epoching into 2 s windows, baseline normalization using the 2 s interval preceding each window, and spatial feature extraction via common spatial patterns (CSP). Log-variance features from four CSP projections were classified using a regularized linear discriminant analysis (rLDA) with automatic shrinkage, trained during calibration runs.

10.3217/978-3-99161-093-9-015

Table 1: Participants' demographic data

	ID	Age	Sex	Diagnosis	AH	Days post-stroke and phase	
EG	PE01	59	F	Hemorrhagic stroke involving the left midbrain and pons	R	42	Early subacute
	PE02	62	F	Acute ischemic stroke involving the right fronto-parieto-temporal regions	L	27	Early subacute
	PE03	60	F	Ischemic stroke involving the R-MCA territory	L	417	Chronic
	PE04	46	F	Hemorrhagic stroke involving the right basal ganglia	L	51	Early subacute
	PE05	69	M	Subacute ischemic stroke involving the R-MCA territory	L	34	Early subacute
	PE06	61	M	Hemorrhagic stroke involving the left thalamus and left midbrain	R	48	Early subacute
	PE07	49	M	Ischemic stroke involving the L-MCA, L-PCA, R-SCA, L-PICA, and R-PICA	R	20	Early subacute
	PE08	78	M	Ischemic cerebral infarction involving the right PCA territory	L	43	Early subacute
	PE09	84	F	Ischemic cerebral infarction involving the R-MCA territory	L	27	Early subacute
	PE10	79	F	Ischemic cerebral infarction involving the R-MCA territory	L	13	Early subacute
	Mean STD	64.70 12.67	6F, 4M		7L, 3R	72.20 121.77	
CG	PC01	66	M	Ischemic stroke involving the right carotid artery territory	L	110	Late subacute
	PC02	63	F	Ischemic lesions in the right cerebellar hemisphere and basilar artery aneurysm	L	51	Early subacute
	PC03	68	M	Ischemic infarction involving the right hemipons in the PPA territory	L	110	Late subacute
	PC04	88	M	Intracerebral hemorrhage involving the left capsulolenticular region	R	73	Early subacute
	PC05	68	M	Intracerebral hemorrhage involving the left capsulolenticular region	R	83	Early subacute
	PC06	66	F	Acute bihemispheric ischemic cerebral infarctions (mainly left hemisphere)	R	38	Early subacute
	Mean STD	69.83 9.09	2F, 4M		3L, 3R	77.50 29.75	

AH: affected hand, CG: control group, EG: experimental group, F: female, M: male, R: right, L: left, MCA: middle cerebral artery, PCA: posterior cerebral artery, SCA: superior cerebellar artery, PICA: posterior inferior cerebellar artery, PPA: paramedian pontine artery.

Participants were allocated to a control group (CG, $n = 6$) receiving conventional rehabilitation or to an experimental group (EG, $n = 10$) receiving additional BCI-based therapy.

Conventional rehabilitation: It followed the hospital's standard multidisciplinary stroke program and included individualized physiotherapy, occupational therapy, neuropsychological intervention, and speech/swallowing therapy when clinically indicated. Physiotherapy focused on motor recovery, balance, gait, tone management, and upper-limb mobilization, whereas occupational therapy targeted activities of daily living and upper-limb dexterity.

BCI-based therapy: The BCI intervention consisted of 23 one-hour sessions delivered five times per week. Initial sessions (3) provided visual feedback only for familiarization, whereas subsequent sessions (20) combined visual and robotic feedback. To reduce frustration and facilitate engagement during early exposure to the system, calibration runs were performed using positive feedback, whereby the virtual hand closed independently of classifier performance. This familiarization strategy was intended to help participants understand the task and progressively develop control over the MI paradigm before receiving fully contingent feedback. Each session included structured training and testing runs within a cue-based MI paradigm, with continuous real-time feedback provided during imagery periods.

In the first session, the calibration phase comprised 4 runs (40 trials total; 20 left-hand and 20 right-hand MI trials). In subsequent sessions, calibration consisted of 2 runs (20 trials total), which were combined with the 120 trials acquired during the previous session to retrain the decoding model. To mitigate EEG non-stationarities and preserve stable online performance, the CSP+rLDA pipeline was recalibrated after 40 and 80 trials during each session. No additional cross-validation or hyperparameter tuning procedures were applied, since the objective of the study was to evaluate feasibility under real-time clinical conditions using a fixed decoding pipeline. During online operation, overlapping 2 s epochs were processed every 200 ms to produce probabilistic estimates of left- versus right-hand MI, which were used to drive continuous real-time feedback.

Motor, cognitive and functional assessments: Pre- and post-intervention assessments encompassed standardized measures of motor function, cognitive performance, and functional independence administered by certified clinicians. Motor function was assessed by FMA [7], Box and Block Test (BBT) [8] and Range of Motion (ROM) goniometry for wrist and fingers [9]. Cognitive tests comprised the Free and Cued Selective Reminding Test (FCSRT) [10] and the Rey-Osterrieth Complex Figure (ROCF) [10]. Functional status was assessed by the 36-Item Short Form Health Survey (SF-36) [11], as well as the Functional Independence Measure (FIM) [12].

RESULTS AND DISCUSSION

Table 2 summarizes the statistical outcomes of the motor, cognitive, and functional assessments at pre- and post-intervention in both the CG and EG. For cognitive measures, z-scores were computed using normative data adjusted for age, education, and sex from Spanish populations [10]. Within-group pre–post differences were assessed with one-sided Wilcoxon signed-rank tests, whereas between-group comparisons of change scores were performed using one-sided Mann–Whitney U tests. All p-values were adjusted for multiple comparisons using the Benjamini–Hochberg false discovery rate proce-

 10.3217/978-3-99161-093-9-015

Table 2: Statistical results for motor, cognitive and functional tests.

Type	Test		Measure	μ_{CG1}	μ_{CG2}	p_{CG}	μ_{EG1}	μ_{EG2}	p_{EG}	Δp
Motor	FMA	↑	Upper Extremity (score)	11.167	14.000	0.362	17.100	22.600	**0.041**	0.814
		↑	Wrist (score)	2.500	2.833	0.630	2.900	4.100	0.186	0.814
		↑	Hand (score)	3.667	4.833	0.362	4.800	6.900	**0.041**	0.814
		↑	Coordination / Speed (score)	1.167	1.667	0.372	1.700	2.200	0.125	0.814
		↑	Global (score)	20.167	29.167	0.302	25.000	33.600	**0.032**	0.814
	BBT	↑	Affected Hand (no. blocks)	11.167	13.333	0.372	6.700	11.900	0.053	0.814
		↑	Non affected Hand (no. blocks)	29.833	34.333	0.302	29.100	32.500	**0.047**	0.814
	ROM	↑	Palmar Flexion (º)	17.500	27.500	0.362	21.000	32.500	**0.041**	0.814
		↑	Dorsal Flexion (º)	7.500	12.500	0.362	10.500	15.500	0.125	0.814
		↑	Radial Deviation (º)	5.833	8.333	0.372	6.500	8.500	0.186	0.814
		↑	Ulnar Deviation (º)	4.167	8.333	0.372	8.500	11.000	0.186	0.814
		↑	Index MCP Flexion (º)	23.333	45.833	0.362	40.500	53.500	0.082	0.816
		↑	Index MCP Extension (º)	10.833	15.833	0.372	12.000	15.000	0.186	0.814
		↑	Thumb Abduction (º)	25.833	32.500	0.372	24.000	32.000	0.082	0.814
		↑	Thumb Adduction (º)	0.000	5.000	0.630	3.000	6.500	0.617	0.814
		↑	Thumb MCP Flexion (º)	10.000	19.167	0.362	23.500	32.000	0.186	0.814
		↓	Thumb Opposition (cm)	0.667	0.917	1.000	1.700	1.700	0.698	0.814
Cognitive	FCSRT	↑	Immediate Free Recall 1 (z-score)	-0.492	-0.417	0.590	-0.816	0.697	**0.032**	0.461
		↑	Immediate Free Recall Total (z-score)	-0.825	-0.075	0.302	-0.190	0.597	0.053	0.814
		↑	Total Recall (z-score)	-0.760	0.168	0.372	-0.438	0.936	0.053	0.814
		↑	Delayed Free Recall (z-score)	-0.917	-0.175	0.372	-0.087	1.412	**0.032**	0.814
		↑	Delayed Total Recall (z-score)	0.007	0.760	0.372	-0.044	1.520	**0.032**	0.814
	ROCF	↑	Copy (z-score)	-0.994	-0.600	0.453	-1.609	-0.200	**0.032**	0.814
		↓	Time (z-score)	-0.594	-1.134	0.302	-0.955	-0.676	0.769	0.947
Functional	SF-36	↑	Physical Function (score)	1.667	10.833	0.302	22.000	30.000	0.053	0.814
		↑	Role (score)	0.000	0.000	1.000	12.500	27.500	0.186	0.814
		↑	Role Emotional (score)	16.667	27.667	0.372	23.300	43.300	0.330	0.814
		↑	Vitality (score)	35.000	50.833	0.302	54.000	60.000	0.281	0.923
		↑	Mental Health (score)	47.333	56.000	0.302	66.800	68.800	0.290	0.837
		↑	Social Function (score)	31.500	46.000	0.302	53.850	72.700	0.076	0.814
		↑	Bodily Pain (score)	70.000	80.333	0.372	74.700	89.400	0.125	0.814
		↑	General Health (score)	50.000	54.167	0.362	46.000	57.500	**0.041**	0.814
	FIM	↑	Total (score)	62.500	80.333	0.302	82.900	96.700	**0.032**	0.881

MCP: metacarpophalangeal; FMA: Fugl–Meyer Assessment; BBT: Box and Block Test; ROM: Range of Motion goniometry; FCSRT: Free and Cued Selective Reminding Test; ROCF: Rey–Osterrieth Complex Figure Copy Test; SF-36: 36-Item Short Form Health Survey; FIM: Functional Independence Measure. Columns μ_{CG1} and μ_{EG1} denote pre-assessment means, and μ_{CG2} and μ_{EG2} post-assessment means for control (CG) and experimental (EG) groups, respectively. p_{CG} and p_{EG} are within-group pre–post comparison p-values, and Δp is the p-value for between-group comparison of change scores $(CG_2 - CG_1)$ vs. $(EG_2 - EG_1)$. Arrows indicate the expected direction of improvement (↑ increase, ↓ decrease). P-values were adjusted column-wise using the Benjamini–Hochberg false discovery rate procedure. One-sided Wilcoxon signed-rank tests were used for within-group comparisons, and a one-sided Mann–Whitney U test for the between-group comparison.

dure. The hypothesized direction of improvement for each metric is also indicated.

Overall, the analyses indicated significant pre–post gains in the EG across several subscales, whereas the CG did not exhibit significant changes. Because both groups received conventional rehabilitation and only the EG completed the additional BCI-based intervention, the observed within-group improvements in the EG may suggest a potential additive effect of the proposed BCI system beyond usual care. However, the absence of statistically significant between-group differences, together with the unequal and limited sample sizes, precludes drawing firm conclusions regarding superiority of the BCI intervention. In addition, several measures also showed numerical improvements in the CG, suggesting that spontaneous recovery, conventional rehabilitation, or limited statistical power may also contribute to the observed effects.

Motor effects: Regarding motor improvements, EG demonstrated significant motor improvements across global FMA ($\Delta = 8.60$, $p = 0.032$) and FMA-UE ($\Delta = 5.50$, $p = 0.041$), indicating enhanced voluntary motor control and coordination; as well as improvements in the FMA hand subscale ($\Delta = 2.10$, $p = 0.041$), suggesting better distal dexterity and grasp–release capacity. A significant increase in palmar flexion ($\Delta = 11.50°$, $p = 0.041$) further supports functional hand positioning. Interestingly, BBT performance improved significantly for the unaffected limb, with a positive trend for the affected side. This pattern may reflect task familiarization effects, compensatory increases in use of the unaffected limb during daily activities, and/or limited statistical power. The magnitude and direction of the FMA-UE effect were consistent with prior meta-analytic findings on BCI-based rehabilitation, including robotic-based [4, 5] and FES-based paradigms [13]. Notably, the observed standardized effect size was comparable to those reported for FES-based BCIs, despite the use of combined robotic

 10.3217/978-3-99161-093-9-015

and visual feedback in the present protocol [13]. Collectively, these findings could point to motor benefits associated with the proposed BCI-based intervention.

Cognitive effects: Significant neuropsychological improvements were also observed in the EG, particularly in verbal episodic memory and visuoconstructive abilities. On the FCSRT, participants demonstrated enhanced immediate learning and uncued retrieval ($\Delta = 1.51$, $p = 0.032$), greater delayed spontaneous retrieval ($\Delta = 1.50$, $p = 0.032$), and higher delayed total recall ($\Delta = 1.56$, $p = 0.032$); indicating more efficient encoding, retention, and retrieval processes. Performance on the ROCF copy condition ($\Delta = 1.41$, $p = 0.032$) also improved significantly, suggesting better visuospatial organization and planning strategies. Comprehensive cognitive assessment is rarely incorporated into RCTs of MI–based BCI interventions in stroke, and such outcomes are largely absent from existing meta-analyses, limiting direct comparisons. Although analogous MI-based neurofeedback studies in elderly populations have documented cognitive gains across multiple domains [14, 15], these effects have sometimes been observed in both experimental and control conditions [15], raising the possibility of practice effects or non-specific participant engagement. In contrast, the confinement of cognitive improvements to the EG in the present cohort suggests a potential intervention-specific mechanism, while emphasizing the need for larger, adequately powered trials to establish the robustness and specificity of these findings.

Functional Effects: Finally, the EG demonstrated significant gains in functional outcomes, including improved health-related quality of life and greater independence in activities of daily living. Specifically, SF-36 general health scores increased significantly ($\Delta = 11.50$, $p = 0.041$), reflecting enhanced self-perceived well-being, although comparable data are largely absent from prior BCI-based stroke rehabilitation studies. FIM scores also improved significantly ($\Delta = 13.80$, $p = 0.032$), indicating reduced assistance requirements in daily functioning. The magnitude of FIM change was consistent with previous MI-based BCI interventions incorporating robotic feedback [16], while existing meta-analytic evidence reports considerable heterogeneity in functional outcome measures [4], which may obscure pooled effects. Overall, the observed improvements support enhancement in everyday functional autonomy.

Strengths and limitations: Recent commercial rehabilitation systems such as recoveriX [17] demonstrated the clinical potential of MI-based BCI paradigms combined with FES for promoting active muscular activation after stroke. In comparison, the present approach employed multimodal robotic and visual feedback, which may provide a more kinematically congruent and anatomically controlled sensorimotor experience during hand movements. While FES directly activates residual musculature, robotic assistance may facilitate more reproducible joint trajectories and movement amplitudes, particularly in patients with severe paresis. Both approaches should therefore not be considered mutually exclusive. Future work could investigate hybrid paradigms integrating robotic assistance and FES in order to combine active muscular recruitment with synchronized proprioceptive and visual feedback.

The findings suggest that the proposed BCI-based therapy incorporating multimodal feedback may facilitate motor recovery and confer additional cognitive and functional benefits beyond those achieved with conventional rehabilitation in stroke patients. However, we acknowledge that the study's modest sample size ($n = 16$) limited statistical power and precluded subgroup analyses based on clinically relevant variables such as affected side or hand. Furthermore, the absence of longitudinal follow-up prevents conclusions regarding the durability of observed gains. Future research should investigate the durability of these improvements. Additional efforts may focus on the implementation of more advanced signal processing and adaptive decoding techniques, alongside strategies to enhance user engagement and perceived sense of agency through augmented reality integration and, where appropriate, the incorporation of gamification elements to promote sustained motivation and participation. In addition, recovery stage was heterogeneous across participants. Notably, the two late-subacute participants were allocated to the CG, whereas the EG included one chronic participant. Since spontaneous recovery dynamics differ substantially across recovery phases, this heterogeneity may have influenced group-level outcomes.

Another important limitation is that the experimental group received additional therapy exposure in the form of 23 BCI sessions, whereas the control group only received conventional rehabilitation. Since motor imagery itself may promote motor recovery after stroke, part of the observed improvements may reflect non-specific training effects independent of neural decoding accuracy. At the same time, it would not be ethically appropriate to withhold conventional rehabilitation from the EG in order to isolate the effect of the BCI intervention, as conventional rehabilitation constitutes the current standard of care for stroke rehabilitation. Future studies should therefore incorporate intensity-matched control conditions, such as sham-feedback or robotic-only interventions added to conventional therapy, in order to better isolate the specific therapeutic contribution of the BCI feedback while maintaining equivalent rehabilitation exposure across groups.

CONCLUSION

This study investigated the effects of a noninvasive MI–based BCI delivering combined visual avatar and robotic-assisted feedback in post-stroke rehabilitation. Over 23 one-hour sessions, participants receiving the BCI intervention (EG, $n = 10$) in addition to standard multidisciplinary therapy exhibited significant pre–post improvements in upper-limb motor performance, selected cognitive domains, and functional independence, whereas no significant changes were detected in the

 10.3217/978-3-99161-093-9-015

participants receiving conventional therapy alone (CG, $n = 6$). Motor gains encompassed clinically relevant Fugl–Meyer subscales and palmar range of motion, while cognitive improvements were observed in verbal episodic memory and visuoconstructive performance. Functional outcomes also improved, as reflected by enhanced self-perceived health status and greater autonomy in daily activities. Although between-group comparisons did not reach statistical significance, potentially owing to limited sample size and unequal therapy exposure between groups, the consistent pattern of within-group improvements in the EG cohort suggests a potential additive therapeutic effect associated with intention-contingent multimodal feedback and sensorimotor closed-loop. Overall, these preliminary findings suggest that MI-based BCI interventions may promote not only motor recovery but also cognitive and functional gains, particularly in subacute stroke populations.

ACKNOWLEDGMENTS

This research was mainly supported by the project RTC2019-007350-1 funded by Ministry of Science and Innovation of Spain, and partially by project 0124_EU-ROAGE_MAS_4_E, funded by EU-ERDF through the Interreg VI-A Spain-Portugal Program (POCTEP) 2021-2027; and VA140P24, by the Regional Goverment of Castilla y León and EU-ERDF. This work was supported by 'Centro de Investigación Biomédica en Bioingeniería, Biomateriales y Nanomedicina (CIBER-BBN)' through 'Instituto de Salud Carlos III' co-funded with EU-ERDF funds. A. Martín-Fernández was in receipt of a PIF grant by the 'University of Valladolid'. We would also like to acknowledge the Benito Menni Hospital Center in Valladolid (Spain) for its assistance in recruiting participants and for its support in the implementation of the evaluation protocol.

REFERENCES

[1] Feigin VL et al. World Stroke Organization: Global Stroke Fact Sheet 2025. International Journal of Stroke. 2025;20(2):132–144.

[2] Angerhöfer C, Colucci A, Vermehren M, Hömberg V, Soekadar SR. Post-stroke Rehabilitation of Severe Upper Limb Paresis in Germany – Toward Long-Term Treatment With Brain-Computer Interfaces. Frontiers in Neurology. 2021;12:772199.

[3] Langhorne P, Coupar F, Pollock A. Motor recovery after stroke: A systematic review. The Lancet Neurology. 2009;8(8):741–754.

[4] Li D et al. Effects of brain-computer interface based training on post-stroke upper-limb rehabilitation: A meta-analysis. Journal of NeuroEngineering and Rehabilitation. 2025;22(1):44.

[5] Cervera MA et al. Brain-computer interfaces for post-stroke motor rehabilitation: A meta-analysis. Annals of Clinical and Translational Neurology. 2018;5(5):651–663.

[6] Santamaría-Vázquez E et al. MEDUSA©: A novel Python-based software ecosystem to accelerate brain-computer interface and cognitive neuroscience research. Computer Methods and Programs in Biomedicine. 2023;230:107357.

[7] Fugl-Meyer AR, Jääskö L, Leyman I, Olsson S, Steglind S. A method for evaluation of physical performance. Scand J Rehabil Med. 1975;7(1):13–31.

[8] Mathiowetz V, Volland G, Kashman N, Weber K. Adult norms for the Box and Block Test of manual dexterity. The American journal of occupational therapy. 1985;39(6):386–391.

[9] Srinayanti Y, Widianti W, Andriani D, Firdaus FA, Setiawan H. Range of motion exercise to improve muscle strength among stroke patients: A literature review. International Journal of Nursing and Health Services (IJNHS). 2021;4(3):332–343.

[10] Palomo R et al. Spanish normative studies in young adults (NEURONORMA young adults project): Norms for the Rey–Osterrieth Complex Figure (copy and memory) and Free and Cued Selective Reminding Test. Neurología (English Edition). 2013;28(4):226–235.

[11] Ware Jr JE. SF-36 health survey update. Spine. 2000;25(24):3130–3139.

[12] Ottenbacher KJ, Hsu Y, Granger CV, Fiedler RC. The reliability of the functional independence measure: A quantitative review. Archives of physical medicine and rehabilitation. 1996;77(12):1226–1232.

[13] Ren C et al. 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. 2024;18:1438095.

[14] Gomez-Pilar J, Corralejo R, Nicolas-Alonso LF, Álvarez D, Hornero R. Neurofeedback training with a motor imagery-based BCI: Neurocognitive improvements and EEG changes in the elderly. Medical & Biological Engineering & Computing. 2016;54(11):1655–1666.

[15] Marcos-Martínez D et al. Motor imagery-based neurofeedback in older adults: Neural signatures and feasibility in a randomized controlled trial targeting age-related cognitive decline. Journal of NeuroEngineering and Rehabilitation. 2026;23(1):107.

[16] Zanona AdF et al. Brain-computer interface combined with mental practice and occupational therapy enhances upper limb motor recovery, activities of daily living, and participation in subacute stroke. Frontiers in neurology. 2023;13:1041978.

[17] Irimia D et al. recoveriX: A new BCI-based technology for persons with stroke. In: 2016 38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC). IEEE: Orlando, FL, USA, Aug. 2016, 1504–1507.