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Post-Stroke Upper- and Lower-Limb Rehabilitation Through Brain-Computer Interface, Robotic Devices and Transcranial Alternating Current & Functional Electrical Stimulations

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Abstract - This work presents the application of a rehabilitation protocol using a Brain-Computer Interface (BCI) based on Motor Imagery (MI) and Neurofeedbak (NF) and applying transcranial Alternating Current Stimulation (tACS) and Functional Electrical Stimulation (FES) together with the use of robotic devices like a robotic monocycle and a robotic glove. This protocol uses the concept of Alternating Treatment Design (ATD), in which a single chronic post-stroke patient is submitted to these techniques. The rehabilitation progress was analysed through EEG and clinical metrics, such as Fugl-Meyer Assessment Scale (FMS), Functional Independence Measurement (FIM), Modified Ashworth Scale (MAS), MiniBESTest (MBT), modified Rankin Scale (mRS), Time Up and Go (TUG), 10-Meter Walk Test (10MWT), National Institutes of Health Stroke Scale (NIHSS), Barthel Scale (BI), and surface electromyography (sEMG). Results from these metrics include 6% increase in Fugl-Meyer Assessment Scale (FMS) for upper-limb and 9% increase for lower-limb; 8% increase in Functional Independence Measurement (FIM), and with the an improvement in the FIM score from 5.83 to 6.27; 25% increase in MiniBESTest (MBT); 30% decrease in Time Up and Go (TUG); 18% increase in time and 25% increase in number of steps in 10-Meter Walk Test (10MWT); 25% decrease in NIHSS; and 14% increase in BI . However, there was not variation, comparing the initial and the final evaluation, for the metrics MAS (which maintained the Grade 1) and mRS (maintaining a score of 3). Regarding the results for surface Electromyography (sEMG), there were 5% increase in muscle contraction peak for finger flexors, 2% for tibialis anterior and 21% for rectus femoris. For the EEG analysis, topographic maps show increase of energy in mu and beta rhythms at the end of intervention, and results also indicate that the use of NF enhances MI performance compared to MI alone.

***Keywords*:** Stroke, Neurorehabilitation, Brain-Computer Interface, Transcranial Alternating Current Stimulation, Functional Electrical Stimulation, Robotic Devices.

1. Introduction

A study by the United Nations forecasts that, by 2050, the population of individuals aged 65 and older will reach 1.5 billion, constituting 16% of the total population [1]. This demographic shift is accompanied by an increase in age-related health concerns, notably stroke, as the likelihood of experiencing a stroke doubles roughly every 10 years after turning 55 [2]. Stroke, a clinical condition marked by insufficient blood flow to the brain, leads to cell death. Stroke can be ischemic (80% of cases), caused by reduced blood flow, or haemorrhagic, due to bleeding, whose impact largely depends on the location and its severity. Individuals recovering from a stroke may face varying degrees of neural injury affecting motor functions in both upper- and lower-limbs [3].

The effects of a stroke on the upper-limb can be a weakness (hemiparesis) or paralysis (hemiplegia) on one side of the body (often seen on the opposite side to where the stroke occurred); loss of fine motor skills of fingers and hands; spasticity (increased muscle tone or stiffness in the affected arm); sensory changes (such as numbness, tingling, or a "pins and needles" sensation); and difficulty with the coordination of shoulder, elbow, wrist, and fingers. On the other hand, the lower-limb effects can be weakness or paralysis (similar to the upper-limb) in one leg, affecting the ability to walk and perform weight-bearing activities; impaired balance and coordination while standing and walking, increasing the risk of falls; spasticity (due to tightness and stiffness in the muscles of the affected leg, making walking and movement challenging); foot drop (the foot cannot be lifted properly due to weakness or paralysis of the muscles that control dorsiflexion (lifting the foot upwards), which can lead to dragging the foot while walking); and altered gait patterns (such as a limp, scissoring gait – legs crossing over each other –, or circumduction – swinging the leg out to the side while walking) [3]. After a stroke, rehabilitation for impairments in both the upper- and lower-limbs typically consists of a blend of physical therapy, occupational therapy, and sometimes speech therapy. The goal is to improve strength, range of motion, coordination, and functional abilities to enhance independence in Activities of Daily Living (ADL) [4],[5].

Early intervention is vital for optimal outcomes in upper- and lower-limb rehabilitation, capitalizing on the brain's adaptability known as "neuroplasticity". Traditional therapies focus on strength, range of motion, motor control, and ADL performance [6]. Such therapies form the foundation, but advancements like technology-enhanced therapies offer new possibilities for optimizing training intensity, repetition, progress evaluation, and patient-specific treatment [7].

Recent years have shown innovations that can transform post-stroke rehabilitation, such as the use of robot-assisted therapy, which provides feedback and tracks progress for personalized rehabilitation [7],[8]. Other novelties in this field are the use of Functional Electrical Stimulation (FES) and transcranial Alternating Current Stimulation (tACS). FES induces peripheral activation to enhance muscle contraction, through suitable pulse amplitude, duration and frequency, to generate stimuli triggering action potentials in intact peripheral nerves [9], and tACS regulates brain oscillations and reshapes brain rhythms [10]. Rehabilitation involving a Brain-Computer Interface (BCI) is another innovation that provides a groundbreaking approach. In fact, BCI establishes direct communication between the brain and the rehabilitation equipment [11]. Moreover, studies have shown that BCIs based on Motor Imagery (MI) of upper- and lower-limb movements can improve motor learning and increase neural plasticity [12-13]. These motor patterns can be analysed through Event-Related Synchronization (ERS)/Desynchronization (ERD), which are associated to indicate neural changes, specifically a power increase or decrease in the brain's electrical signals, respectively [14]. Thus, BCIs can translate these detected MI into commands for external devices, enhancing motor function and independence for stroke survivors [5]. As part of such MI-BCI therapy, the inclusion of NF has shown improvements in neuroplasticity, as this technique measures and shows to the subject their brain wave activity to help them self-regulate their brain function and enhance specific targets [15].

2. Materials and Methods

Fig. 1 shows the methodology used in our study for upper- and lower-limb post-stroke rehabilitation through a BCI, robotic devices, tACS and FES.

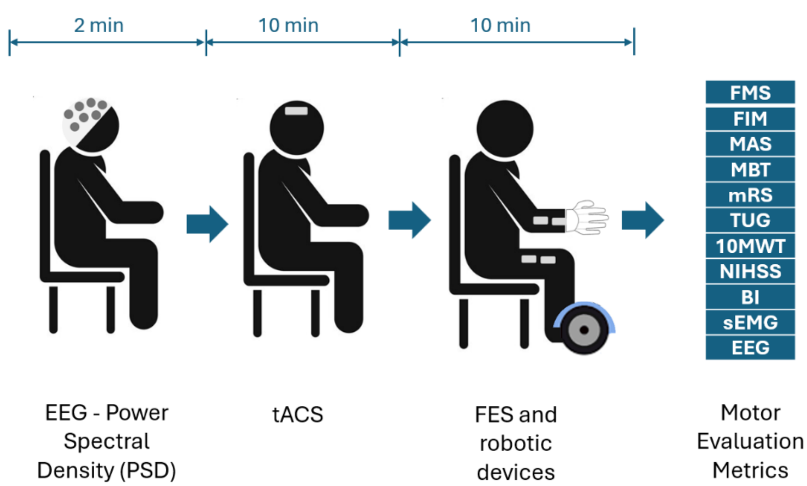
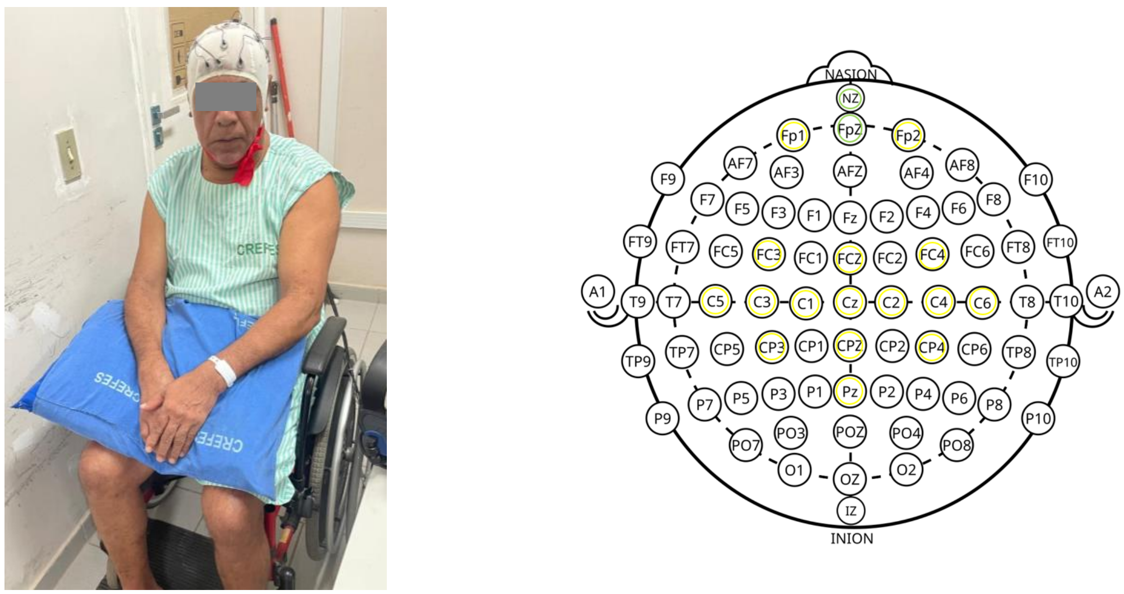


Fig. 1: Methodology applied in this study.

2.1 Patient characteristics

The patient of our study is a 64-year-old man who had an ischemic stroke in October 2024, small vessel type, according to the Trial of Org 10172 in Acute Stroke Treatment (TOAST) classification [16]. His risk factor was non-treated hypertension. CT scan of his brain showed a lacunar ischemic stroke in the left capsular nucleus region. His electrocardiogram exam showed sinus rhythm, the presence of atrioventricular conduction disturbance, and non-sustained ventricular tachycardia. His echocardiogram showed no abnormalities. The patient was informed in detail of the activities conducted during the experiments and subsequently voluntarily signed the informed consent form, following the Declarations of Helsinki. The Ethics Committee of the Federal University of Espirito Santo (UFES/Brazil) approved the experiment under the number CAAE:39410614.6.0000.5060. Fig. 2 (a) shows the patient wearing the EEG cap, which is used to recognize MI patterns when imaging limb movements.



(a) (b)

Fig. 2: (a) Patient wearing the EEG cap from OpenBCI to start the experiments; (b) Electrode location on the EEG Cap from OpenBCI.

2.2 Measuring MI frequencies

To acquire EEG signals, an wireless signal acquisition board (Open BCI Cyton-Daisy, USA) is used, which samples at 125 Hz signals from sixteen EEG electrodes located on: Fp1, Fp2, FC3, FCz, FC4, C5, C3, C1, Cz, C2, C4, C6, CP3, CPz, CP4, and Pz, and with two references at Nz and Fpz, such as shown in Fig. 2 (b).

In the patient of this study, cortical activity during MI and MI+NF conditions was analysed through Relative Power Changes (P) in the mu (8–12 Hz) and beta (18–24 Hz) bands. The value of P for each electrode was computed in 1-s windows based on FFT values for these bands. EEG signals were processed online in real time, utilizing a 1-s window with 500 ms overlap for data segmentation [17-20]. Preprocessing included Laplacian Average Reference (LAR) filtering to reduce interference at C3 and C4, along with a 4th-order zero-phase Butterworth band-pass filter (7–30 Hz). The normalized power band, P_s, was calculated for each 1-s window "i" and electrode "e" using Eq. (1).

$$P_{s_{e,i}} = \left[\frac{\frac{\left(P_{\mu}^{i} + P_{\beta}^{i}\right)}{2}}{P_{8-30}^{i}} \right]_{e}, \qquad (1)$$

where $P_{s_{e,i}}$ is the normalized power band on each electrode "e" on the 1-s-window "i" during mental state "s". In this stage, "e" corresponds to C3 and C4. P_{μ}^{i}, P_{β}^{i} and P_{8-30}^{i} are power bands in μ (8-12 Hz), β (18-24 Hz), and full range (8-30 Hz). A subtraction between $P_{s_{e,c_4}}$ and $P_{s_{e,c_3}}$ is calculated and an interpolation was considered to show this subtraction as VNF on the screen with (2).

$$\Delta P_{s_{e,i}}(\%) = \left|\frac{P_{MI} - \overline{P_{ba}}}{\overline{P_{ba}}}\right| \times 100, \quad (2)$$

where $\Delta P_{s_{e,i}}$ represents the normalization including MI trials as well as the mean P from the baseline period of all trials.

Once the patient has worn the EEG cap, he was instructed to imagine moving his paralyzed arm (left arm) for 2 min. To determine the frequency associated with his MI, the EEG data was processed in EEGLab/Matlab for mu and beta rhythms (from 8 to 30 Hz). EEG was evaluated in terms of energy increase in the rhythms mu and beta, which are related to MI.

2.3 tACS application

In each session, tACS is applied to the patient for 10 min and with current intensity of 0.4 mA. This application is done bilaterally, through conductive rubber electrodes (35 cm^2), which are connected to perforated sponges soaked in saline solution connected to the tACS device (NeuroMyst Pro, USA). Fig. 3a-3c show the patient receiving tACS. It worth mentioning that during the tACS application the patient is instructed to conduct MI of the paralyzed limbs while watch a videoclip showing a person strolling in a field (Fig. 3c).

(a) (b) (c)

Fig. 3: Patient receiving tACS: a) frontal view; b) details of electrode location; c) videoclip shown to motivate MI.

2.4 FES and robotic devices

Once the tACS procedure is completed, the patient is prepared for the next step of the protocol, which is to receive electrical stimulation from the FES device and passive movements from the robotic monocycle and robotic glove during Motor Imagery (MI). For the electrical stimulation, an FES device (Balego EMS Digital Neuromuscular, USA) was used to target the finger flexors and extensors simultaneously, with the following parameters: alternating mode, 1-s ramp, 7-s on-time, 12-s off-time, frequency of 45 Hz, and pulse width of 250 µs. For the rectus femoris and tibialis anterior muscles, the following parameters were used: synchronous mode, 1-s ramp, 7-s on-time, 12-s off-time, frequency of 60 Hz, and pulse width of 300 µs. The stimulation intensity was adjusted based on the patient's comfort level.

Fig. 4 shows the patient with the FES electrodes attached to his paralyzed arm and leg, as well as his hand wearing the robotic glove and his feet on the robotic monocycle. Thus, whenever the patient performs MI, he receives electrical stimulation and passive movements on the paralyzed limbs. The approach to recognize the patient's MI was based on our previous work [21].

(a)


(b)

Fig. 4: Patient receiving electrical stimulation from the FES device, and passive movements from the robotic monocycle and robotic glove: a) details of FES electrode location on the paralyzed arm and leg; b) paralyzed hand worn with the robotic glove, and feet on the robotic monocycle.

2. 5 Motor Evaluation Metrics

The patient's rehabilitation progress was evaluated in terms of his motor ability through the following metrics: Fugl-Meyer Assessment Scale (FMS), Functional Independence Measurement (FIM), Modified Ashworth Scale (MAS), MiniBESTest (MBT), modified Rankin Scale (mRS), Time Up and Go (TUG), 10-Meter Walk Test (10MWT), National Institutes of Health Stroke Scale (NIHSS), Barthel Index (BI), and surface electromyography (sEMG). These metrics are described in Table 1.

Table 1. Metrics used to evaluate the patient's rehabilitation progress.

Metric	Acronym	Description
Fugl-Meyer Assessment Scale	FMS	The measures are based on neurological examination and sensorimotor activity of the upper and lower-limbs, seeking to identify the selective activity and synergistic patterns of patients who have suffered stroke [22]. Six aspects are evaluated: range of motion, pain, sensitivity, upper and lower extremity motor function, and balance, as well as coordination and speed. This scale has a total of 126 points for the upper-limb assessment, and 100 points for the lower-limb, totalling 226 points. To assess the percentage of recovery the following equation is used: $\%\,recovery = \frac{Score\ Obtained\ x\ 100}{C}$; where C = 126 for upper limb and C = 100 for lower limb.
Functional Independence Measurement	FIM	Assesses a person's performance in the motor and cognitive/social domains feeding, personal hygiene, bathing, dressing the upper half of the body, dressing the lower half of the body, toilet use, urine control, fecal control, transfers to bed, chair, wheelchair, toilet transfers, bath or shower transfers, locomotion, stair locomotion, comprehension, expression, social interaction, problem solving, and memory [23]. Each of these items varies in seven levels with level 7 being total independence, and level 1 total dependence, modified independence (level 6), moderate dependence with the need for supervision or preparation (level 5) or with direct help (levels 1 to 4). A person without any disability achieves a score of 126 points, and one with total dependence scores 18 points. The more dependent, the lower the score.
Modified Ashworth Scale	MAS	To assess the intensity of hypertonia and therapeutic response the muscle resistance to passive movement is evaluated in degrees, as follows: Grade 0: classified as no increase in muscle tone; Grade 1: slight increase in muscle tone, manifested by grasping and releasing, or by minimal resistance at the end of the range of motion, when the affected limb (or limbs) is moved in flexion and extension; Grade 1+: slight increase in muscle tone, manifested by apprehension, followed by minimal resistance through the rest (less than half) of the range of motion; Grade 2: marked increase in muscle tone through most of the range of motion, but the affected limbs are easily moved; Grade 3: considerable increase in muscle tone, hindered passive movements; Grade 4: the affected limb (or limbs) are stiff on flexion or extension [24].
MiniBESTest	MBT	14 items that are grouped into four items: 1) Anticipatory postural adjustments; 2) Reactive postural responses; 3) Sensory orientation; 4) Gait stability with and without a cognitive task. Each item is scored on a three-point scale: from zero (worst performance) to two (best performance). The total score is 28 points, indicating that there is no deficit in dynamic balance. If the individual scores below 28 points, it means that there is a deficit. This test is useful for screening for deficits in dynamic balance and can be applied to individuals affected by various diseases and of any age [25].
modified Rankin Scale	mRS	To assess the patient's level of disability globally, and, consequently, their level of functional dependence the levels of disability are classified as: 0: No symptoms; 1: No significant disability; 2: Mild disability; 3: Moderate disability; 4: Moderately severe disability; 5: Severe disability; 6: Death [26].
Time Up and Go	TUG	A functional mobility test that assesses gait, in function of postural and direction changes during the act of walking. The test consists of getting up from a chair with a backrest, without supporting the arms, walking 3 m, turning around, returning and sitting down again. TUG is used to assess the risk of falls. The time spent to perform this metrics is measured, which generates a risk classification, being low risk of falling (< 10 s), medium risk of falling (10-20 s), and high risk of falling (> 20 s) [27].

10-Meter Walk Test	10MWT	An assessment of a person's mobility, speed, and ability to walk. This test consists of walking 10 m as fast as possible, without running. During the test, the time to cover the 10 m is timed, as well as the number of steps needed to complete the course [28].
National Institutes of Health Stroke Scale	NIHSS	An indicative of impairment level. This scale is composed of 11 items, each of which scores a specific ability between a 0 and 4 [29]. For each item, a score of 0 indicates normal function while a higher score is indicative of some level of impairment. The individual scores from each item are summed to calculate a patient's total score. The maximum possible score is 42, with the minimum score being a 0.
Barthel Index	BI	An index of independence to accomplish ADL. The scale describes 10 tasks (feeding, bathing, grooming, dressing, bowel, bladder, toilet use, transfers bed-to-chair-and-back, mobility on level surfaces, and stair negotiation), which is scored according to amount of time or assistance required by the patient. Total score is from 0 to 100, with lower scores representing greater nursing dependency [30].
Surface Electromyography	sEMG	A technique that analyses the electrical activity of muscles. It is a non-invasive and painless method that can be used to monitor and assess muscle contraction [31].
Electroencephalograpy	EEG	A technique that provides a direct measure of the functional neuroelectric activity in the brain, forming the basis for neuroplasticity and recovery of post-stroke patients, increasing prognostic ability [32].

3. Results

3.1 MI frequencies

Maximum values of Power Spectral Density (PSD) were found in frequencies of 8 and 30 Hz, as shown in Fig. 5. However, based on studies by [10], more efficiency of tACS is found for frequencies in beta band. Thus, we select 30 Hz as the stimulation frequency for the tACS device.

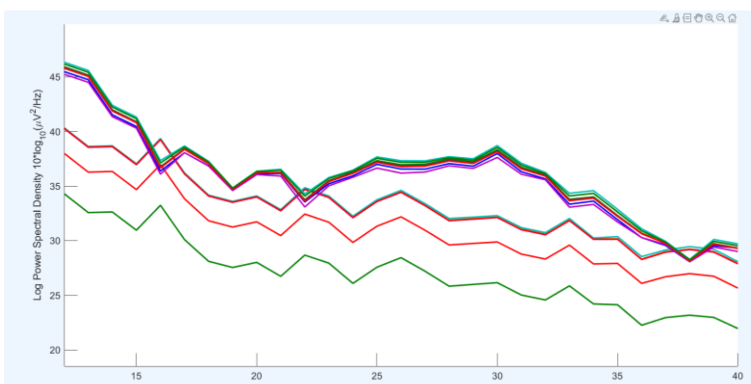


Fig. 5: PSD of EEG signals for mu and beta rhythms (from 8 to 40 Hz).

3.1 Motor Evaluation Metrics

Using FMS, the results indicate a gain of about 6% (Fig. 6a) in the recovery of his upper-limb function (functionality, range of motion, sensitivity, pain, proprioception and speed). The FMS for lower-limb was also applied, with the patient improving 12.7% from the initial evaluation to the final evaluation (Fig. 6b). For FIM, the patient got about 8% increase from the initial to the final evaluation (about 8% increase). Also, in the initial evaluation the patient was evaluated with a score of 5.83 (moderate dependence with the need for supervision or preparation), whereas in the final evaluation, he improved his scored to 6.27, classifying him as a condition of "modified independence" (Fig. 6c). Related to MAS, the patient presented Grade 1 in both the initial and final evaluation (Fig. 6d). For MBT, two out of the four items were evaluated, which were item 1 and item 2, where the total score is 12 points. Thus, in the initial evaluation, the patient achieved a total score of 4 points (moderate balance deficit), whereas in the final evaluation, he achieved 5 points (moderate balance deficit) (Fig 6e), meaning 25% increase. For mRS, in the initial evaluation and final evaluation the patient achieved a score of 3 form mRS metric (Fig. 6f). Related to TUG metric, in the initial evaluation, the volunteer lasted 55 s to perform the TUG, whereas in the final evaluation he reached 39 s (Fig. 6g). It is worth mentioning that although in both evaluations the patient remained at high risk of falling (time >20 s), there was a significant reduction in the time to perform the test (reduction of 16 s, i.e., ≃ 30% in the time to perform the TUG when compared to the initial evaluation). For 10MWT metric, in the initial evaluation the patient lasted a time of 27.33 s to walk 10 m (gait speed of 0.37 m/s), with approximately 16 steps. In the final evaluation, he lasted a time of 32.33 s (gait speed of 0.31 m/s), with approximately 20 steps, resulting in 18% increase in time, and 25% increase in number of steps to walk 10 m. Fig. 6h-6i show these results. Related to NIHSS metric, in the neurological physical examination at the initial evaluation, the patient presented right hemiparesis, with grade 2 strength in his right hand, grade 3 in the rest of the right upper-limb, and grade 3 in his right lower-limb, scoring a 4 on NIHSS. In the final evaluation, he scored 3, representing 25% decrease (Fig. 6j). For BI, in the initial neurological physical examination, the patient presented 36 points on BI, whereas in the final evaluation he scored 41, representing 14% increase (Fig. 6k).

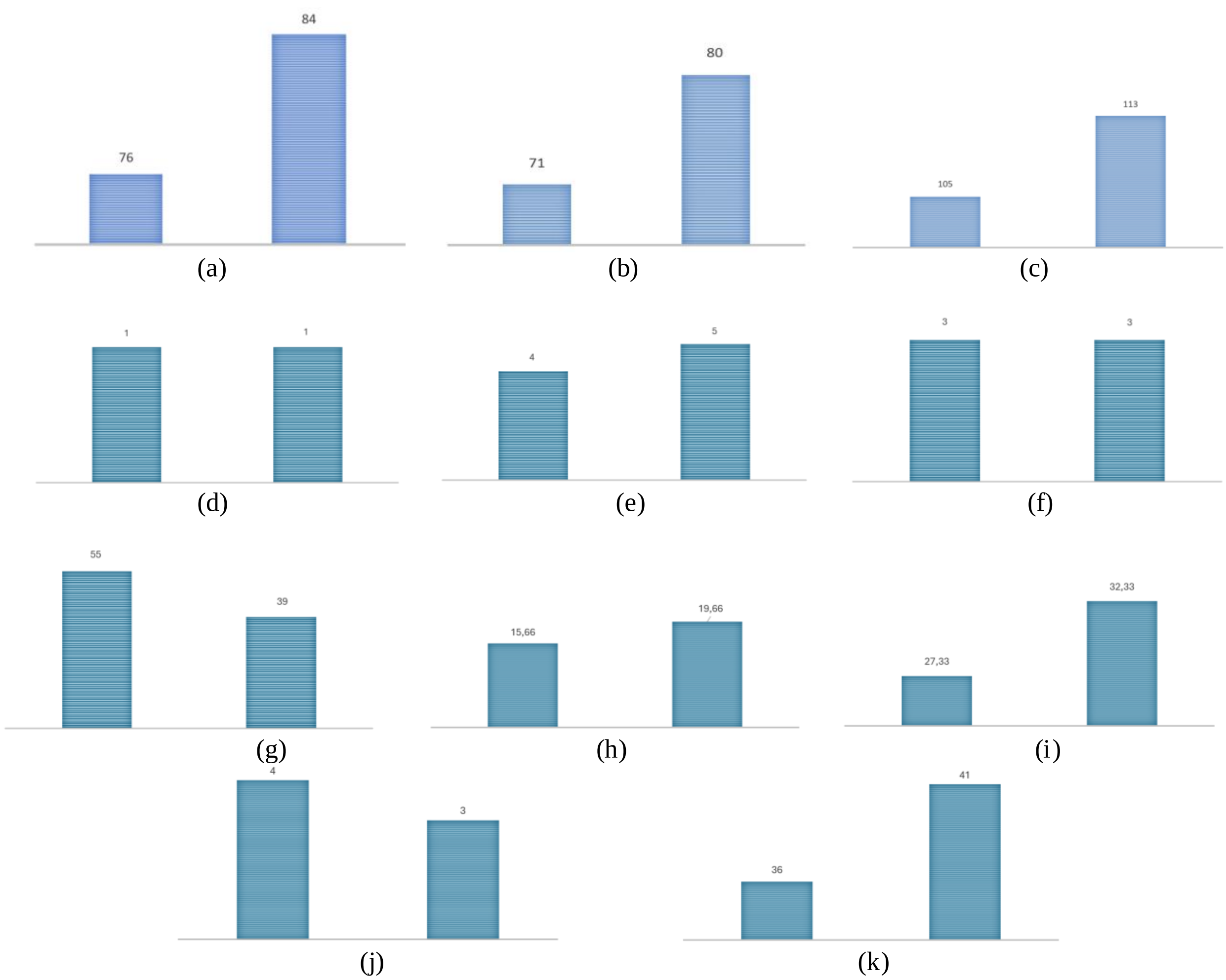


Fig. 6: Comparison between initial (left) and final (right) evaluation for: a) FMS for upper-limb; b) FMS for lower-limb; c) FIM; d) MAS; e) MBT; f) mRS; g) TUG; h) 10MWT for number of steps; i) 10MWT for spent time; j) NIHSS; k) BI.

3.10 sEMG

In the patient of this study, his peak of muscle contraction of fingers' flexor, extensors, rectus femoris and tibialis anterior muscles were evaluated. An improvement in the muscle contraction of the finger flexors was observed, which had a peak of 78.35 µV in the initial evaluation, and 82.23 µV in the final evaluation (Fig. 7a), representing ≃5% increase. The tibialis anterior muscle presented a peak of 64.92 µV in the initial evaluation, and 66.06 µV in the final evaluation (Fig. 7b), representing ≃2% increase, and the rectus femoris muscle had a peak of 110.02 µV in the initial evaluation, and 133.43 µV in the final evaluation (Fig. 7c), representing ≃ 21%. However, the fingers' extensor muscles did not show improvement in this evaluation.

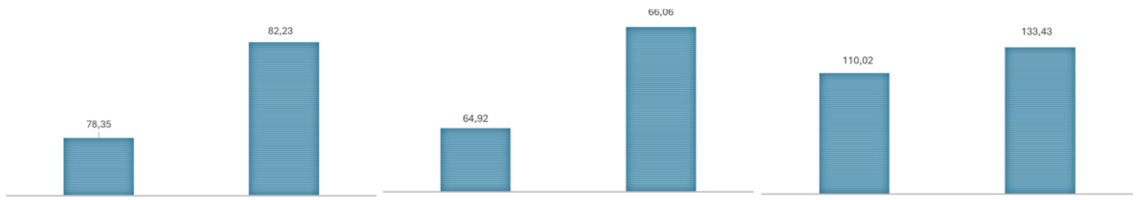


Fig. 7: sEMG measurements for the following muscles: a) finger flexors; b) tibialis anterior; c) rectus femoris.

3.11 EEG

Fig. 8 illustrates the mean P values in C3 and C4 during motor imagery (MI) and neurofeedback (NF) trials, analysed across mu, low-beta, and high-beta frequency bands.

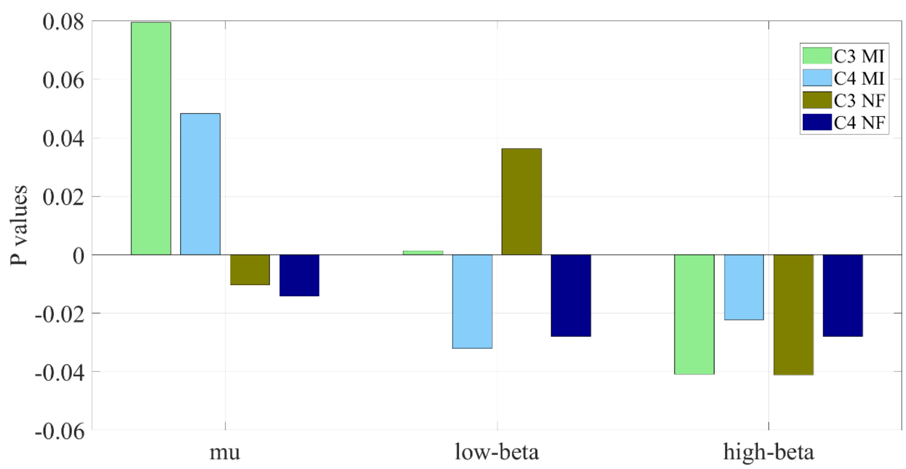
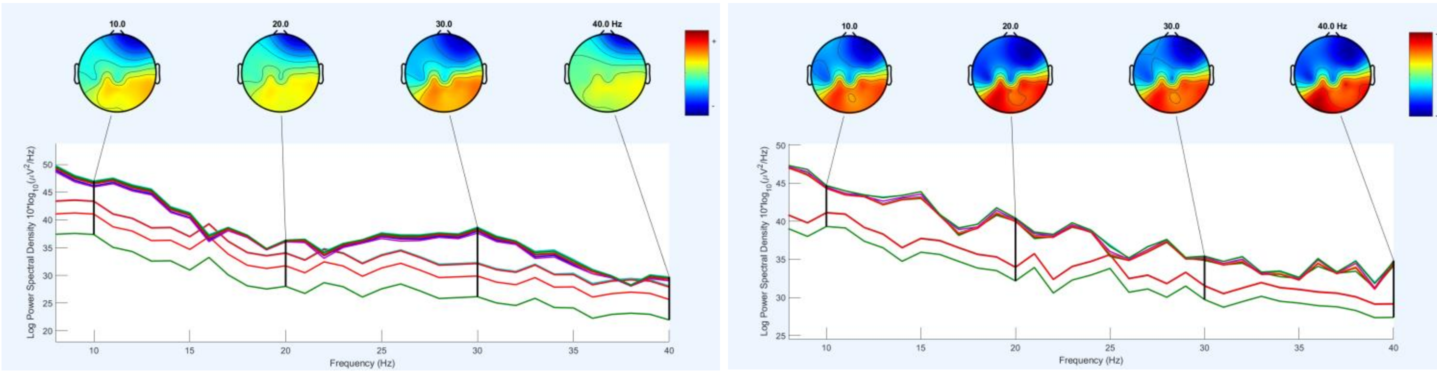


Fig. 8: Mean P values in C3 and C4 during MI and NF trials.

In the mu band, P values in C3 and C4 decreased during NF, reaching negative values, whereas they remained positive during MI without feedback. In the low-beta band, P values increased in C3, but became negative in C4 when comparing MI and NF. In contrast, high-beta exhibited a distinct pattern, with consistently negative P values in both C3 and C4 across MI and NF conditions, though lower P values were observed during NF. Negative P values suggest stronger engagement or Event-Related Desynchronization (ERD), which is often desirable in MI-based BCIs, reinforcing the idea that NF enhances MI performance compared to MI alone. Regarding the energy variation in mu and beta bands, Fig. 9 shows the topographic maps captured before and after the intervention, in which it is possible to see the increase of energy (red colour) at the end of intervention.



(a) (b)

Fig. 9: Topographic maps for EEG signals in mu and beta bands: a) Before the therapy; b) After the therapy.

4. Discussion and conclusions

Results of this study demonstrate that the patient improved his condition at the end of the intervention (except for the 10-Meter Walk Test (10MWT), where he had 18% increase in time and 25% increase in number of steps). In all addition metrics he had 6% increase in Fugl-Meyer Assessment Scale (FMS) for upper-limb and 9% increase for lower-limb, 8% in Functional Independence Measurement (FIM), and passing from a FIM score of 5.83 to 6.27, 25% increase in MiniBESTest (MBT), 30% decrease in Time Up and Go (TUG), 25% decrease in NIHSS, and 14% increase in BI. However, there was not variation, comparing the initial and the final evaluation, for the metrics MAS (which maintained the Grade 1) and mRS (maintaining a score of 3). Regarding the results for surface Electromyography (sEMG), there were 5% increase in muscle contraction peak for finger flexors, 2% for tibialis anterior and 21% for rectus femoris.

For the EEG analysis, topographic maps show increase of energy in mu and beta rhythms at the end of intervention, and results also indicate that the use of NF enhances MI performance compared to MI alone.

We believe these improvements were due to our therapy, which facilitated neuromodulation, enhancing the excitability of the motor cortex and improving muscle activation, as well as reducing spasticity and allowing for greater voluntary contraction during evaluations.

It is worth commenting that there is a limitation in this study, which evaluated only a single participant. On the other hand, this study does not present comparisons with other studies, as we believe that this is the first study using a combination of tACS, MI-BCI-NF, FES and robotic devices for post-stroke rehabilitation. Therefore, more studies are needed to confirm the results with a wider sample, as well as conducting the research by blinded evaluators.

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