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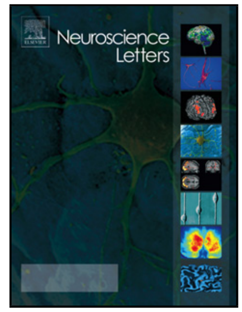

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DIAGONAL MOVEMENT OF THE UPPER LIMB PRODUCES GREATER ADAPTIVE PLASTICITY THAN SAGITTAL PLANE FLEXION IN THE SHOULDER

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HIGHLIGHTS

- The effects of PNF on the brain's electrical activity
- PNF generates greater changes in cortical activity, as assessed by beta band absolute power levels
- PNF generates greater neural recruitment for the execution of maneuvers, when compared with shoulder flexion in the sagittal plane alone.

ABSTRACT

The motor rehabilitation is based on exercises that involve various joints and muscle groups. One such treatment method is Proprioceptive Neuromuscular Facilitation (PNF), which involves diagonal movements simulating many activities of daily living. The objective of this study was to investigate the differences between PNF and shoulder flexion movements performed without the diagonal component (i.e., only in the sagittal plane) using beta band absolute power as a measure of plasticity. The study included 30 volunteers randomized into three groups (control, PNF, and FLEX), with electroencephalographic signals captured before and after the performance of the task. The PNF group showed an increase in beta band absolute power in both hemispheres, indicating greater plasticity than that seen in the FLEX group. Therefore, PNF seems to be capable of promoting cortical adaptations that lead to the recruitment of both hemispheres, thus influencing cortical organization in more complex tasks.

Key words: Electroencephalography, PNF, Rehabilitation, Nervous System

INTRODUCTION

Movement is a fundamental mechanism for conducting activities of daily living, including getting up, cooking, and driving to work, amongst other things. Any restriction in the execution of movements implies a decline in an individual's physical capacity. Movement is essential for human beings to have a good quality of life, and for physical and cognitive improvement if any functional loss is experienced in the limbs [1, 2, 3]. Although the mechanisms underlying movements are inherent in human beings, movements themselves are differentiated according to the joint and muscle groups recruited for their implementation [4]. Therefore, understanding the mechanisms involved in the execution of movements, for example cortical activity, is critical for regaining lost functionality in [5, 6].

Voluntary movement improves with practice and produces modulations in the brain's electrical activity in accordance with the complexity of the motor task [7, 8]. Features in the environment and sensory information also influence motor activity. As a result, changes in the brain areas involved in planning and executing motor tasks, processing of sensory information, and the integration of information also need to be investigated [9, 10]. It is noteworthy that the performance of motor tasks involves different neural circuits responsible for the planning and execution of movement, as well as the integration of environmental information associated with the task, thus improving its implementation [11, 12].

One treatment concept involving diagonal patterns is Proprioceptive Neuromuscular Facilitation (PNF) [4]. Diagonal movements that cross the midline of the body are more functional because they simulate movements performed in daily life, thus optimizing the rehabilitation process [4, 13]. Movements that are easier for the individual to perform possess a plastic, more well-defined, pattern that facilitates their evocation [14, 15, 16, 17]. At a cortical level, the facilitation positions increase evoked motor potentials, thus increasing the movement's effectiveness [4, 18]. Nevertheless, the differences in cortical activity in response to peripheral pulses related to movements performed without diagonal components are still unknown. Although other electroencephalography (EEG)-based studies have investigated various plastic conditions in the cortex [19, 20, 21, 22], the neurophysiological cortical behaviors involved in PNF have not yet been investigated.

Despite studies demonstrating the effects of PNF on increasing strength [5, 23], and muscle recruitment, etc., no clear cortical differences between PNF and movements performed in the sagittal plane (FLEX) have yet been observed. The specific functioning of cortical areas is represented by changes in the frequency bands and other electroencephalographic variables, such as absolute power (AP) [24]. AP is the energy produced in the cortex, and it is modulated according to the condition/task imposed on the subject. These measurements can be analyzed in the frequency range between 13 and 30Hz, corresponding to the beta band [24], which is associated with motor behavior [25, 26]. The cortical potential related to movement can be used to analyze brain excitability-related voluntary motor potentials, and is mainly associated with cortical processes before or immediately after the initiation of movement. However, the importance of studying these potentials at the end of the movement should also be noted [27].

Thus, the aim of this study was to investigate the differences in the electrophysiological responses triggered by PNF and shoulder flexion movements performed without the diagonal component (i.e., just in the sagittal plane) on cortical electrical activity. The differences were analyzed using the cortical potentials produced by motor tasks before and after the execution of movements, specifically through the beta band absolute power levels produced in the dorsolateral prefrontal cortex (DLPFC), primary motor cortex (M1), and parietal cortex (PC). We hypothesized that PNF diagonal upper limb movement would produce a greater increase in absolute beta band power than flexion in the sagittal plane alone.

MATERIALS AND METHODS

A self-controlled, cross-sectional study was conducted at the Brain Mapping and Functionality Laboratory (LAMCEF) of the Federal University of Piauí, Brazil. The sample consisted of 30 female participants, 21.36±2.18 years old, all right-handed (Edinburgh Handedness Inventory) [28], sedentary [29], and with a body mass index (BMI) between 18.50 to 24.99 kg/m² (23±2.27). To ensure greater sample homogeneity in the level of muscle strength, we selected only female students.

The exclusion criteria included musculoskeletal and joint disorders in the upper limb, and any cardiac, pulmonary, or neurological diseases. Individuals with functional limitations in the performance of resistance movements, amputees, and those with sensory or cognitive deficits that limited the performance of movements were also excluded. With regard to the EEG, participants could not have used psychoactive drugs or have slept less than eight hours the night before the experiment. Participants who met the inclusion criteria and agreed to participate in the experiment were informed about the experimental procedure and research confidentiality, and signed a consent form. The study was approved by the Ethics Committee of the Federal University of Piauí (Opinion No.1, 087,478/2015).

Electroencephalography

The EEG signal was captured using a BrainNet BNT 36-EEG (EMSA-Medical Instruments, Brazil). An elastic cap, average adult size (54–58 cm), with electrodes arranged according to the international 10–20 system and an elastic strap for attachment, was used for recording. The reference electrodes were placed on the earlobes (biauricular). The recording room was isolated acoustically and electrically, and the impedance of the skin-electrode interface was kept below 10 kΩ. The data acquired had total amplitude below 100 μV. The EEG signal was passed through an analog filter between 0.1Hz (high-pass) and 100Hz (low-pass), and scanned at 400Hz. With the acquisition and control software (developed in Delphi 5.0), the raw data were digitally filtered with a 60Hz notch, a 0.3Hz high-pass, and a 30Hz low-pass.

Experimental procedure

Participants were randomized into three groups: control: no performance of movement during the task interval, i.e., at rest; PNF: starting with the wrist and fingers, the participant flexed the hand on the contralateral leg in order to simulate the starting position standardized by PNF, i.e., the participant performed an extension of the wrist and fingers, extension of the elbow with flexion, abduction and external rotation in the right upper limb (Figure 1A); FLEX, upper limb flexion, abduction and rotation, held in the sagittal plane, i.e., the hand was initially placed on the ipsilateral leg with the wrist and fingers in flexion (Figure 1B).

Participants received instructions from a physiotherapist and were trained in the correct performance of the maneuver prior to the experiment. The movement was demonstrated by the physiotherapist, and was then performed passively (participant conducted by the physiotherapist), evolving from "*hands on*" to "*hands off*," in which the participant executed the maneuver actively. Once the participant performed the movement correctly (suitable extent and speed), the main procedure was initiated. The task was performed in a light- and sound-attenuated room to reduce sensory interference. The participants sat comfortably in a chair to minimize muscular artifacts while the EEG signal was captured.

Upon receiving a visual stimulus on an 18.5-inch monitor positioned in front of them, the participant performed the requested task, repeating it 81 times. To determine the number of repeats, previous tests were carried out with 60 participants involving the tasks proposed in this study, and the participants rated their perceived exertion using a 20-point Subjective Perception of Effort Scale [30]. The group that performed 81 repetitions had average values below the 11–13 ("fairly light" to "somewhat difficult") score recommended for sedentary and untrained individuals [31], not limited to the correct execution of the maneuver. The study design is summarized in Figure 2. The tasks were performed only in the dominant limb, with the participant's feet on the floor and their hip in 90° flexion, and they were instructed to keep the trunk of their bodies resting on the chair to minimize artifacts. The EEG signal was captured immediately before and after the tasks, and each collection lasted three minutes. During data capture, subjects were instructed to remain at rest.

Data Processing

Visual inspection and an independent component analysis (ICA) were applied to identify and remove all EEG artifacts [32, 33]. The ICA was applied to separate the source signals on the scalp, and was performed by means of an extension of EEGLAB. Participants whose data showed problems, such as the presence of artifacts and noise in the electroencephalographic signal, were excluded. The electrode data that showed loss of contact with the scalp or high impedance (>10kΩ) were not included. A classic estimator was applied to the power spectral density (DPE), estimated from the Fourier transformation, which was performed using MATLAB R2009b (Mathworks, Inc.).

Statistical analysis

The study measured absolute beta band power before and after the tasks. Selected derivations were related to the DLPFC (F3, F4), M1 (C3 and C4), and PC (P3 and P4). Thus, a two-way analysis of variance (ANOVA) was performed for the beta band with three intergroup factors (Control×PNF×FLEX), and two intragroup moment factors (before×after the task).

To evaluate whether the assumptions of a two-way ANOVA were met, Mauchley's test, which evaluated sphericity, and the Greenhouse-Geisser procedure (G-Gε), which corrected for degrees of freedom, were used. Data normality and homoscedasticity were previously verified using Levene’s and Shapiro-Wilk tests, respectively ($p>0.05$ for both). The interactions between factors were investigated using one-way repeated measures ANOVA with a *post-hoc* Bonferroni test. The effect size was estimated as *partial eta squared* ($\eta^2 p$). The statistical power and the 95% confidence interval (95% CI) were calculated for the dependent variables. However, when the one-way repeated measures ANOVA was analyzed separately for group and moments, statistical significance was set at a Bonferroni-adjusted alpha-level of $p=0.008$. The effect magnitude was interpreted using the recommendations suggested by Hopkins *et al.*, (2009) [34]: 0.0=trivial; 0.2=small; 0.6=moderate; 1.2=great; 2.0=very large; 4.0=almost perfect. A 5% probability for type I errors was adopted in all analyses ($p=0.05$). Thus, to detect if there was a real difference in the population, the statistical power was interpreted as 0.8 to 0.9, i.e., high power [35]. Analyses were conducted using SPSS for Windows version 20.0 (SPSS Inc., Chicago, IL, USA).

RESULTS

There was a main effect of group in the left DLPFC ($F_{(2,1908)}=81.974$, $p<0.001$, $\eta^2_p=0.79$, power=1.00), but no effect of moment was found. The *post-hoc* test showed a significant difference between the control and PNF groups, with the AP $0.008\mu V^2$

higher (95% CI: 0.006–0.009; $p<0.001$) in the PNF group. The AP in the FLEX group was significantly higher than in controls by 0.003μV^2 (95% CI: 0.001–0.004; $p<0.001$). Similarly, there was a significant difference between the PNF and FLEX groups, with the AP 0.005μV^2 higher (95% CI: 0.003–0.006, $p<0.001$) in the PNF group (Figure 3).

In the right DLPFC, there was a significant interaction between group and moment ($F_{(2,1908)}=9.346$, $p<0.001$, $\eta^2_p=0.01$, power=0.97). The interaction analysis showed a significant difference between the groups before ($F_{(2,954)}=17.537$, $p<0.001$), and after the task ($F_{(2,954)}=23.654$, $p<0.001$). The *post-hoc* test showed a significant difference between the control and PNF groups before the task, with the power 0.003μV^2 higher (95% CI: 0.001–0.004, $p<0.001$) in the PNF group. After the task, the AP was 0.005μV^2 higher (95% CI: 0.002–0.007, $p<0.001$) in the control group compared with the FLEX group. The *post-hoc* test showed a significant difference between the PNF and FLEX groups before the task, with the power 0.003μV^2 higher (95% CI: 0.002–0.005, $p<0.001$) in the PNF group. Similarly, after the task the power was 0.005μV^2 higher (95% CI: 0.002–0.007, $p<0.001$) in the PNF group.

When analyzing the moment factors before and after the task, there was a significant difference in the control group ($F_{(1,636)}=83.395$, $p<0.001$, $\eta^2_p=0.16$, power=1.00), with the power 0.007μV^2 higher (95% CI: 0.006–0.009, $p<0.001$) after the task. There was also a significant difference in the PNF group ($F_{(1,636)}=29.592$, $p<0.001$, $\eta^2_p=0.04$, power=0.001), with the power 0.004μV^2 higher (95% CI: 0.003–0.006, $p<0.001$) after the task. A significant difference was also found in the FLEX group ($F_{(1,636)}=13.522$, $p<0.001$, $\eta^2_p=0.02$, power=0.96), with the power 0.003μV^2 higher (95% CI: 0.001–0.004, $p<0.001$) after the task (Figure 4).

In the left M1, there was a main effect of group ($F_{(2,1909)}=19.315$, $p<0.001$, $\eta^2_p=0.02$, power=1.00) after the task but no effect of moment was found. The *post-hoc* test showed a significant difference between the control and PNF groups, with the power 0.002μV^2 higher (95% CI: 0.001–0.003, $p<0.001$) in the PNF group. A significant difference was also found between the PNF and FLEX groups, with the power 0.003μV^2 higher (95% CI: 0.002–0.004, $p<0.001$) in the PNF group (Figure 5).

In the right M1, there was an interaction between group and moment ($F_{(2.1908)}=6.042$, $p=0.002$, $\eta^2_p=0.02$, power=0.88). The interaction analysis showed a significant difference between the groups both before ($F_{(2,954)}=21.816$, $p<0.001$) and after the task ($F_{(2,954)}=51.247$, $p<0.001$). The *post-hoc* test showed a significant difference when comparing power in the control and FLEX groups before the task; it was $0.003\mu V^2$ higher (95% CI: 0.001–0.005, $p<0.001$) in the control group. The *post-hoc* test showed a significant difference between the control and FLEX groups after the task, with the power $0.007\mu V^2$ higher (95% CI: 0.004–0.009, $p<0.001$) in the control group. Similarly, there was also a difference between the PNF and FLEX groups, with the power $0.005\mu V^2$ higher (95% CI: 0.003–0.007, $p<0.001$) in the PNF group. This difference was also noted after the task, with the power $0.008\mu V^2$ higher (95% CI: 0.006–0.011, $p<0.001$) in the PNF group.

The moment factor analysis showed a significant difference in the control group ($F_{(1,636)}=9.179$, $p=0.003$, $\eta^2_p=0.01$, power=0.86), with the *post-hoc* test showing that the power was $0.003\mu V^2$ higher (95% CI: 0.001–0.004, $p=0.003$) after the task. This was also observed in the PNF group ($F_{(1,636)}=9.423$, $p=0.002$, $\eta^2_p=0.02$, power=0.86), with the power $0.003\mu V^2$ higher (95% CI: 0.001–0.004, $p=0.002$; Figure 6).

In the left PC, there was an interaction between group and moment ($F_{(2.1908)}=20.801$, $p<0.001$, $\eta^2_p=0.02$, power=1.00). The interaction analysis showed a significant difference both before ($F_{(2,954)}=16.635$, $p<0.001$) and after the task ($F_{(2,954)}=13.541$, $p<0.001$). The *post-hoc* test showed a significant difference between the control and PNF groups before the task, with the power $0.003\mu V^2$ higher (95% CI: 0.001–0.005, $p<0.001$) in the control group. After the task, there was a significant difference between the control and FLEX groups, with the power $0.004\mu V^2$ higher (95% CI: 0.002–0.006, $p<0.001$) in the control group. A significant difference was also found between the PNF and FLEX groups, with the power $0.004\mu V^2$ higher (95% CI: 0.001–0.005, $p<0.001$) in the FLEX group before, and $0.003\mu V^2$ higher (95% CI: 0.001–0.005, $p<0.001$) after the task than the PNF group.

The moment factor analysis showed a significant difference in the control group ($F_{(1,636)}=24.317$, $p<0.001$, $\eta^2_p=0.04$, power=0.99), with the *post-hoc* testing showing a power $0.004\mu V^2$ higher (95% CI: 0.002–0.005, $p<0.001$) after the task. This increase was also identified in the PNF group ($F_{(1,636)}=75.370$, $p<0.001$, $\eta^2_p=0.12$, power=1.00), with the power $0.008\mu V^2$ higher (95% CI: 0.006–0.009, $p<0.001$) after the task (Figure 7).

In the right PC, there was an interaction between group and moment factors ($F_{(2.1908)}=29.201$, $p<0.001$, $\eta^2_p=0.03$, power=1.00). The interaction analysis showed a significant difference after the task ($F_{(2,954)}=44.461$, $p<0.001$). The *post-hoc* test showed a significant difference between the control group and the PNF group, with the power $0.003\mu V^2$ higher (95% CI: 0.001–0.004, $p<0.001$) in the PNF group. There was also a significant difference between the control and FLEX groups, with the power $0.005\mu V^2$ higher (95% CI: 0.003–0.007, $p<0.001$) in the control group. The difference between the PNF and FLEX groups was significant, with the power $0.008\mu V^2$ higher (95% CI: 0.006–0.010, $p<0.001$) in the PNF group.

Among the moments before and after the task, there was a significant difference in the control group ($F_{(1,636)}=100.428$, $p<0.001$, $\eta^2_p=0.14$, power=1.00), with the power $0.005\mu V^2$ higher (95% CI: 0.004–0.006, $p<0.001$) after the task. This difference was also found in the PNF group ($F_{(1,636)}=78.942$, $p<0.001$, $\eta^2_p=0.11$, power=1.00), with the power $0.009\mu V^2$ higher (95% CI: 0.007–0.011, $p<0.001$) after the task (Figure 8).

DISCUSSION

The literature has shown beneficial effects of PNF-based diagonal movements at a peripheral level [17, 36]; however, the effects of PNF on the electrical activity of the brain are not yet known. Thus, the objective of this study was to investigate the differences between the cortical electrical effects of PNF and shoulder flexion movements in the sagittal plane alone. The results showed that the initial hypothesis was fulfilled, since the PNF group showed greater absolute power values when compared with the FLEX group, who moved only in the sagittal plane.

The absolute beta band power increase in the DLPFC, especially in the PNF group, suggests a greater need for planning movement execution in diagonal movements, consistent with greater neural adaptation in these regions. This might be associated with the characteristics of the motion which, despite being considered functional movements simulating the daily life of individuals, involve more complex motion sequences [37, 38]. Similarly, the primary motor cortex (M1) also demonstrated increased power in the PNF group, leading us to think that moving diagonally requires greater control of movements and kinesthetic responses. This, in turn, requires greater participation of the motor cortex in movement processing and execution because of muscle recruitment and proprioceptive stimuli [39]. The power increase was also observed in the parietal cortex, suggesting that PNF requires increased cortical activity to integrate the somatosensory information related to the movement [40, 41]. One exception was found for the FLEX group in the right M1 in which the AP was higher before the task. This seems to indicate that, since it is a less complex task, there is less need for bilateral cortical recruitment.

On the other hand, our results also seem to indicate that PNF increased working memory activity, since this function is controlled by the DLPFC, which shows an increase in AP following PNF. Although unclear in the literature, PNF appears to involve the coordination of more difficult motor sequences, and requires greater muscle recruitment and articulation [37,38]. This indicates that more cognitive control and neural plastic adaptation are necessary for PNF [8, 42], so that the motor task may be learned and performed correctly [43]. In addition, PNF may have greater attentional demands than FLEX, given that the movements performed require better coordination, spatial organization, and are new to the individual [44, 45]. Moreover, the power reduction in the FLEX group has the opposite effect to PNF because motor sequence, muscle recruitment, and proprioceptors are required less.

Our results show increased power in both the left and right DLPFC, M1, and PC, indicating that these areas act together in the control of motor tasks at a higher level in the PNF group. Although Derosière *et al*., (2014) [46] and Serrien & Sovijärvi-Spapé (2015) [47] have indicated a role for the contralateral cortex in the control of movement, other studies have indicated effective participation of the ipsilateral cortex by implementing a unilateral motor task with the right upper limb [48,49], as in the present study. In this regard, PNF seems to be capable of promoting cortical adaptations that lead to the recruitment of both hemispheres, thus influencing cortical organization in more complex tasks.

CONCLUSION

PNF generates greater changes in cortical activity, as assessed by absolute power levels in the beta band in the parietal cortex, a cortical region whose functions relate to the integration of motor information. The changes were also found in the dorsolateral prefrontal cortex and the primary motor cortex, revealing that PNF increases neural recruitment for the execution of maneuvers when compared with shoulder flexion in the sagittal plane alone. This suggests possible beneficial effects of PNF at a cortical level, further justifying its use in clinical practice.

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Figure 1. Task: A - PNF. B - FLEX.

Figure 2. Study design

Figure 3. Difference in beta band absolute power in the left dorsolateral prefrontal cortex (DLPFCL)
Data represented as mean and standard error.
* Significant difference between groups.

Figure 4. Difference in the beta band absolute power in the right dorsolateral pre-frontal cortex (DLPFCR)
Data represented as mean and standard error before and after tasks.
* Significant difference between groups
✩ Significant difference between moments

Figure 5. Difference in beta band absolute power in the left primary motor cortex (M1L) after the task
Data represented as mean and standard error.
* Significant difference between groups and moments after the tasks.

Figure 6. Difference in the beta band absolute power in the right primary motor cortex (M1R)
Data represented as mean and standard error before and after tasks.
* Significant difference between groups
✩ Significant difference between moments

Figure 7. Difference in the beta band absolute power in the left parietal cortex (PCL) represented by mean and standard error, before and after task
* Significant difference between groups
✩ Significant difference between moments

Figure 8. Difference in the beta band absolute power in the right parietal cortex (PCR) represented by mean and standard error, before and after task
* Significant difference between groups
✩ Significant difference between moments

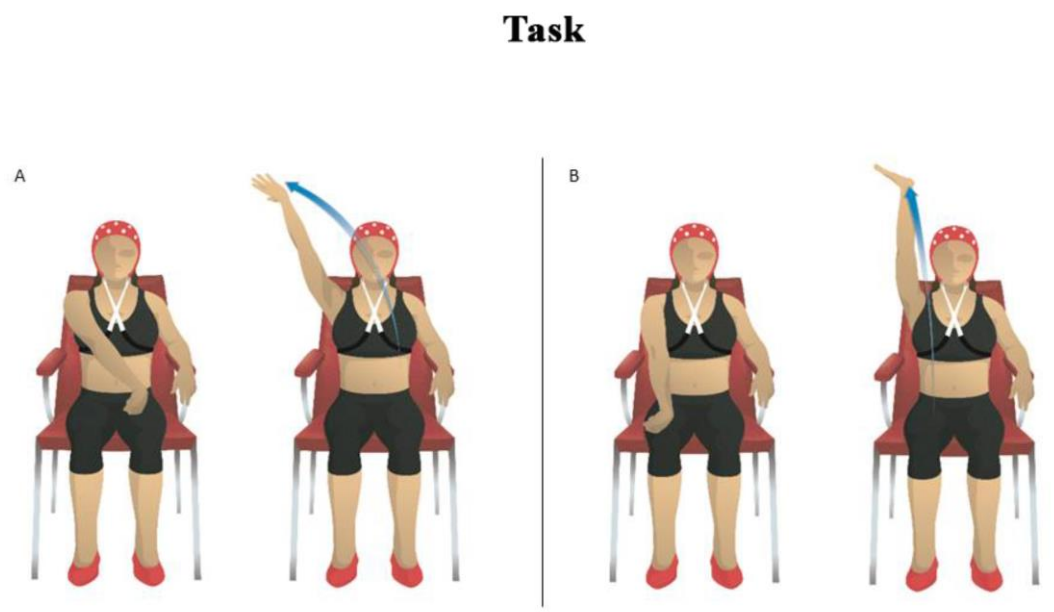
Task
A
B

Fig 1

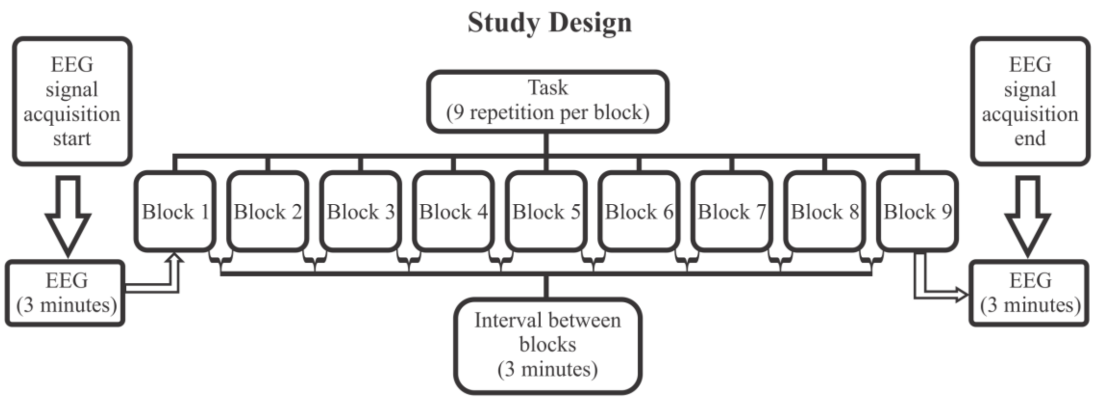
Study Design
EEG signal acquisition start
EEG (3 minutes)
Task (9 repetition per block)
Block 1
Block 2
Block 3
Block 4
Block 5
Block 6
Block 7
Block 8
Block 9
Interval between blocks (3 minutes)
EEG signal acquisition end
EEG (3 minutes)

Fig 2

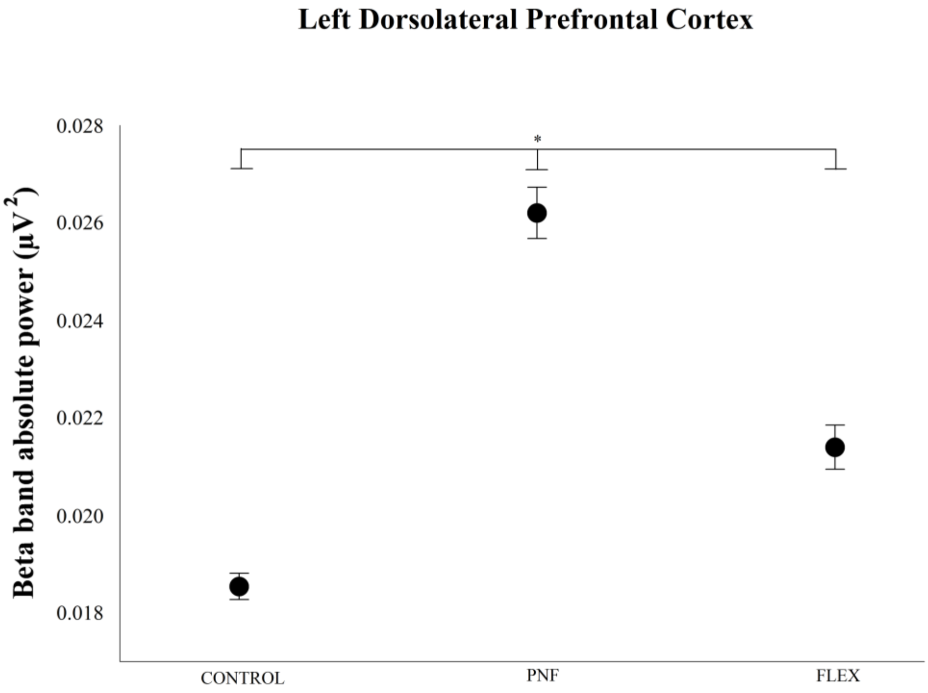
Left Dorsolateral Prefrontal Cortex
Beta band absolute power (μV²)
0.028
0.026
0.024
0.022
0.020
0.018
*
CONTROL
PNF
FLEX

Fig 3

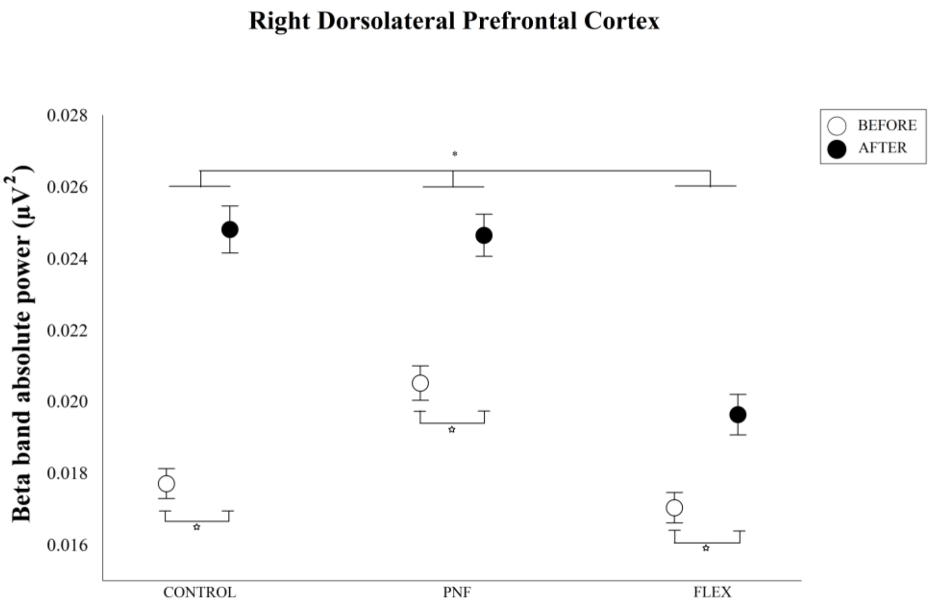
Right Dorsolateral Prefrontal Cortex
Beta band absolute power (μV²)
0.028
0.026
0.024
0.022
0.020
0.018
0.016
BEFORE
AFTER
*
CONTROL
PNF
FLEX

Fig 4

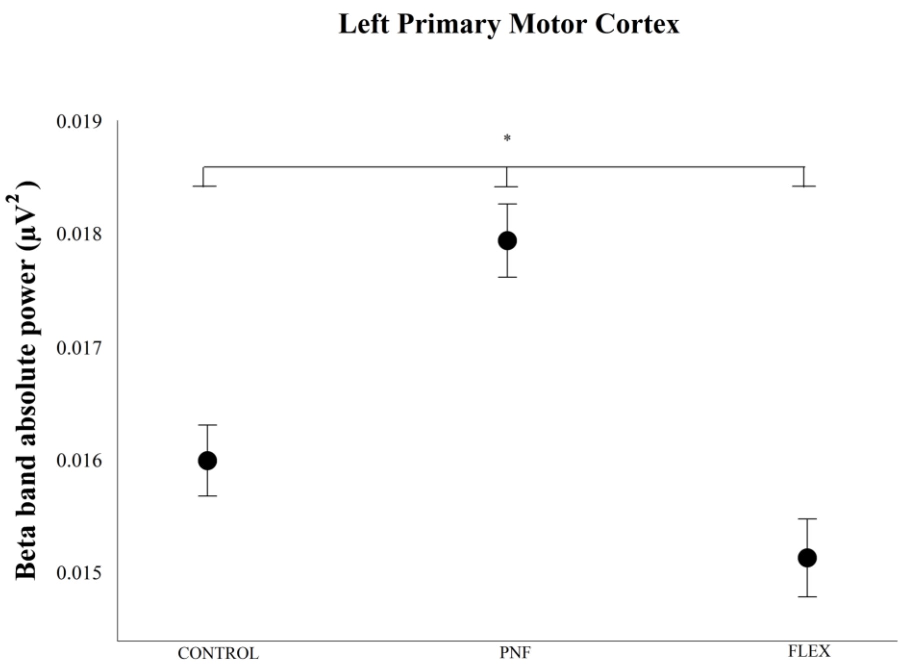
Left Primary Motor Cortex
Beta band absolute power (μV²)
0.019
0.018
0.017
0.016
0.015
*
CONTROL
PNF
FLEX

Fig 5

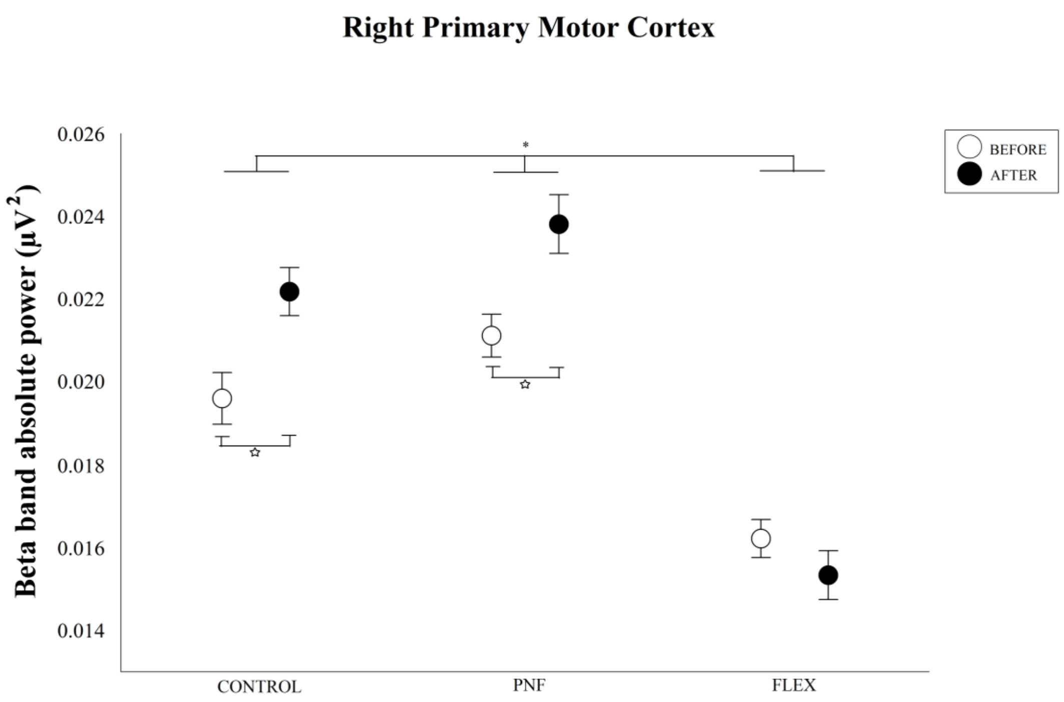
Right Primary Motor Cortex
Beta band absolute power (μV²)
0.026
0.024
0.022
0.020
0.018
0.016
0.014
*
BEFORE
AFTER
CONTROL
PNF
FLEX

Fig 6

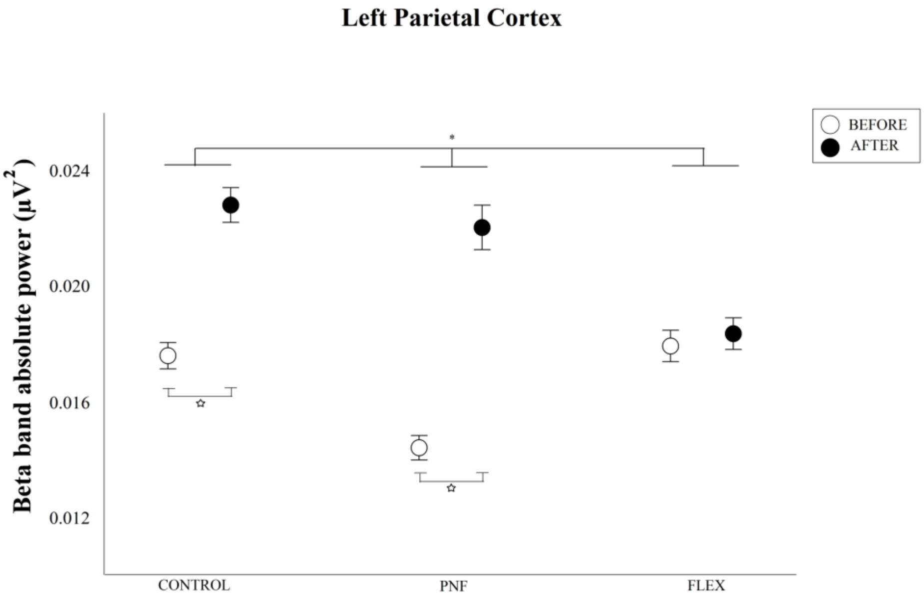
Left Parietal Cortex
BEFORE
AFTER
Beta band absolute power (μV²)
0.024
0.020
0.016
0.012
CONTROL
PNF
FLEX

Fig 7

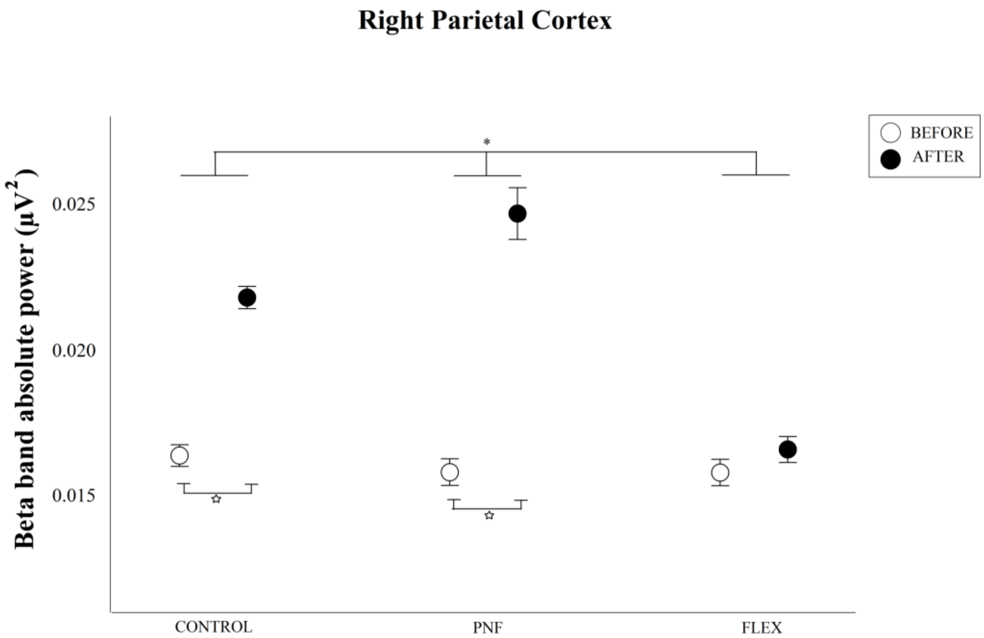
Right Parietal Cortex
BEFORE
AFTER
Beta band absolute power (μV²)
0.025
0.020
0.015
CONTROL
PNF
FLEX

Fig 8