Brain-movement relationship during upper-limb functional movements in chronic post-stroke patients

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Abstract

Background

Following a stroke, brain activation reorganisation, movement compensatory strategies, motor performance and their evolution through rehabilitation are matters of importance for clinicians. Two non-invasive neuroimaging methods allow for recording task-related brain activation: functional near-infrared spectroscopy (fNIRS) and electroencephalography (fEEG), respectively based on haemodynamic response and neuronal electrical activity. Their simultaneous measurement during movements could allow a better spatiotemporal mapping of brain activation, and when associated to kinematic parameters could unveil underlying mechanisms of functional upper limb (UL) recovery. This study aims to depict the motor cortical activity patterns using combined fNIRS-fEEG and their relationship to motor performance and strategies during UL functional tasks in chronic post-stroke patients.

Methods

Twenty-one healthy old adults and 21 post-stroke patients were recruited and realized two standardised functional tasks of the UL: a paced-reaching task where they had to reach a target in front of them and a circular steering task where they had to displace a target using a hand-held stylus, as fast as possible inside a circular track projected on a computer screen. The activity of the bilateral motor cortices and motor performance were recorded simultaneously utilizing a fNIRS-fEEG and kinematics platform.

Results and conclusions

Kinematic analysis revealed that post-stroke patients performed worse in the circular steering task and used more trunk compensation in both tasks. Brain analysis bilateral motor cortices revealed that stroke individuals over-activated during the paretic UL reaching task, which was associated with more trunk usage and a higher level of impairment (clinical scores). This work opens up avenues for using such combined methods to better track and understand brain-movement evolution through stroke rehabilitation.

1. Background

With a very high prevalence, stroke is the second leading cause of death and the first cause of acquired disability in adults in France. Regardless of the severity, strokes frequently result in physical as well as cognitive limitations and compromised quality of life. With 80% of patients experiencing difficulty in using their paretic arm in activities of daily living, upper limb (UL) motor impairment emerges as one of the most frequent disabilities resulting from a stroke (1).

Due to its prevalence, functional non-recovery of the paretic UL is an important focus of rehabilitation management strategies beyond three months post-stroke, specifically in the sub-acute and then chronic stage (2). With difficulties to use their paretic arm for daily activities, patients tend to exhibit non-mandatory trunk compensation (i.e., overuse of trunk flexion, sometimes to the detriment of arm use), particularly evident during forward reaching tasks (3, 4). These phenomena can lead to a learned non-use of the paretic arm (5), potentially encouraging maladaptive brain plasticity (6) and limiting functional recovery of the paretic UL (7). Indeed, functional motor recovery is mainly attributed to plastic reorganization within the human brain (8, 9). Non mandatory motor compensations could significantly impact this brain plastic reorganization (for a review see 10). Thus, investigating how stroke itself affects neural activation during unilateral and bilateral UL activities may elucidate the underlying mechanisms of functional recovery (11).

Chronic stroke patients often demonstrate abnormal brain activation, exhibiting irregular activation in both the ipsi- and contralesional hemispheres during movement. A meta-analysis has reported an increase in activation of the contralesional primary motor cortex, and bilateral premotor and supplementary motor areas when using the paretic hand compared to healthy individuals (12). Additional studies have demonstrated increased contra- and ipsilesional activation during paretic UL movement in stroke patients compared to healthy individuals (13). These studies have highlighted a gradual evolution of these task-related brain activities toward a “normal” lateralized pattern of the primary sensorimotor cortex (SM1 ; 14,15). This pattern is conjectured to correlate with improvements in motor function (16, 17). Specifically, previous work suggested a link between brain reorganization (measured by functional magnetic resonance imaging - fMRI) and functional recovery of the paretic arm during post-stroke rehabilitation (18). Finally, a review evaluating the use of fMRI as a post-stroke prognostic tool suggested that monitoring brain reorganization can enhance our understanding of stroke progression and potentially offer more accurate predictions of patient responses to treatment and rehabilitation (19).

However, a significant limitation of the studies mentioned earlier lies in the incompatibility of the neuroimaging techniques employed with functional movement recordings in ecological conditions. Consequently, the tasks performed under fMRI are not genuinely functional (e.g., thumb-finger opposition task, elbow flexion-extension in the supine position; 20). Post-stroke rehabilitation tends to focus more on movements involving the entire UL (i.e., wrist, elbow, shoulder) in sitting or standing postures, more closely mirroring functional tasks employed in daily life (e.g., reaching and grasping a cup). Thus, assessment of brain activation during upright, unrestrained, functional tasks with alternative portable neuroimaging methods is needed.

In this context, two methods of recording brain activation allow the non-invasive collection of brain signals in an ecological environment while performing functional motor tasks. Firstly, functional near infrared spectroscopy (fNIRS), which is based on indirect recordings of the hemodynamic response of the brain to neuronal activity and relying, like fMRI, on the blood-oxygen level-dependant response, measures oxygenated (HbO_2) and deoxygenated (HbR) blood in the cerebral cortex (21). FNIRS allows brain monitoring in an upright position without physical head restraint as is necessary with fMRI (22). This method has been utilized to measure sensorimotor network activation during UL movements in healthy young adults (23, 24), older healthy adults (24, 25) and stroke patients (11, 26). A limited number of fNIRS studies have investigated proximal UL movements, such as reaching, and generally show a bilateral SM1 activation pattern (24, 28). To the best of our knowledge, only one recent study investigated SM1 activation in a stroke population using fNIRS during a reaching task under ecological conditions (11). They found enhanced ipsi/contralesional SM1 activation in the stroke patients despite poorer motor performance in reaching and grasping. Nevertheless, this study did not measure movement kinematics (i.e., the involvement of trunk compensation, elbow extension, shoulder flexion).

Secondly, fEEG, a method based on the direct recording of brain electrical activity, can measure functional brain activity by detecting variations in electrical currents at the scalp due to local electric fields produced by neuronal activity (29). In this context, event-related power changes within oscillatory neural activities in fEEG signals indicate the level of excitation and inhibition in the sensorimotor network and have been utilized to decode movements (30). This event-related power changes can be observable within specific frequency bands over the SM1 (alpha-mu – 8 to 13 Hz and beta – 14 to 29 Hz). Power oscillations can be characterized by a decrease at movement execution (event-related desynchronization – ERD) or an increase at rest (event-related synchronization – ERS; 31) In subacute stroke patients, a recent study has found a correlation between the magnitude of high-mu and low-beta ERD recorded from the lesioned hemisphere and the residual motor ability in the paretic UL (32). Another study found that higher motor impairment in the paretic UL was related to higher ERD in the unaffected hemisphere (33). More recently, motor dysfunction was proposed to be correlated to ERD on the affected hemisphere during motor task execution (34). Like fNIRS, fEEG could be used to explore task related brain activation patterns during UL movements in stroke patients, and their coupling can lead to a better view of the spatio-temporal information of the brain activation patterns from SM1 over the two hemispheres (35). Finally, we recently showed how complementing brain data with kinematic assessments of functional proximal UL tasks can help to better understand task-related SM1 activity in healthy subjects (24).

The main objective of the present study was to investigate bilateral SM1 activation during a paced reaching task and a circular steering task among people with and without stroke. We hypothesised an increased SM1 activation in the stroke cohort, particularly during the use of the paretic arm in both ipsi- and contralesional hemispheres. The secondary objective of the present study was, to investigate the effect of stroke on the relation between brain activation patterns and motor performance. We hypothesised that individuals in the stroke group would display inferior task performance when using their paretic arm, and that SM1 activation in the lesioned hemisphere would positively correlate with task performance.

2. Material and methods

2.1 Participants

The study cohort consisted of 21 stroke patients and 21 healthy adults. For the stroke group, the inclusion criteria were to: i) be aged between 18 and 90 years old, ii) be at more than 3 months of a first cerebrovascular accident of any aetiology (hemorrhagic or ischemic), and iii) have an UL motor impairment with FM-UE $\geq$ 15 (36). The non-inclusion criteria were to: i) have hemineglect or severe attentional problems (omission of more than 15 bells on the Bell's test; (37), ii) have aphasia of comprehension dysfunction (Boston Diagnostic Aphasia Examination < 4/5; (38), and iii) have severe cognitive dysfunction (Mini Mental State Examination-MMSE < 24; (39). To be included, the healthy adults had to be aged between 60 and 90 years old (to fit with the stroke group age) and to be right-handed assessed by the Edinburgh Handedness Inventory (40). Exclusion criteria were the existence of neurological (including a history of traumatic brain injury) or motor disorders at the level of the upper limb (history of tendinous disease, arthritis, surgery). Healthy participants were recruited via local association, while stroke ones were recruited at the beginning of a rehabilitation protocol (ReArm project, Clinical trial identifier: NCT04291573, 2nd March 2020).

Table 1 provides detailed participant information, including gender, age, lesioned side, laterality, and clinical scores (refer to the clinical assessments section for additional details). For the stroke group, Table 2 presents all patients' demographic data and clinical history.

In accordance with the Declaration of Helsinki, this study was approved from the French Research Ethics Committee, (Comité de Protection des Personnes-CPP SUD-EST II, N°ID-RCB: 2019-A00506-51, http://www.cppsudest2.fr/) for the stroke patients, and from the local Ethics Committee of the EuroMov DHM laboratory for the healthy subjects (EuroMov IRB, number 1912B). All participants provided informed written consent prior participation in the study.

Table 1. Characteristics of the participants for each group (n=21)

Characteristics	*Healthy* group	*Stroke* group
Age (years) (SD)	73.1 (± 6.7)	64.4 (±10.2)
Sex (female/male)	11/10	6/15
Handedness score (SD)	0.96 (± 0.08)	-
Paretic arm (right/left)	-	8/13
FM-UE	-	48.7 (±5.9)
WMFT	-	57.3 (±9.8)
BBT ratio	-	54.0 (±25.1)

BBT ratio = (paretic score / non-paretic score) * 100

Table 2. Demographic information, clinical data, lesion information and clinical scores.

P	*Age*	*Gender*	*Hemisphere lesioned*	*HD before stroke*	*Paretic arm*	*FM-UE*	*BI*	*Type of stroke*
1	62	M	L	R	R	45	85	Is
2	61	M	R	R	L	55	95	Is
3	52	M	R	R	L	51	90	Is
4	63	M	L	L	R	44	95	Is
5	70	M	R	R	L	51	100	Is
6	73	F	R	R	L	53	-	H
7	63	F	R	R	L	27	90	Is
8	57	F	R	R	L	60	90	H
9	74	M	R	R	L	50	85	Is
10	37	M	R	L	L	46	95	Is
11	68	M	R	R	L	47	95	Is
12	76	M	L	R	R	41	90	H
13	62	F	R	R	L	45	85	Is
14	49	F	R	R	L	54	95	Is
15	82	M	L	R	R	58	100	Is
16	72	M	L	R	R	44	90	Is
17	66	M	L	R	R	38	95	Is
18	73	M	L	R	R	36	25	Is
19	71	F	L	R	R	57	95	H
20	62	M	R	R	L	46	-	H
21	60	M	R	R	L	43	90	Is

Abbreviations: M, male; F, female; R, right; L, left; HD, hand-dominance; BI, Barthel index (score/100); FM, Upper Limb Fugl-Meyer (score/66); Is, Ischemic; H, Hemorrhagic. The severity of the motor impairment was evaluating using the FM-UE in accordance with the motor impairment classification in clinical and research settings (41).

2.1 *Experimental design*

Each participant engaged in an hour-long session in a quiet isolated room. The participants were equipped with the fNIRS-fEEG neuroimaging systems and performed two functional UL tasks while seated: a paced reaching arm task and a circular steering task. The setup permitted synchronized recording of UL kinematics and brain activity (fNIRS and fEEG) using lab streaming layer (LSL, https://github.com/labstreaminglayer/App-LabRecorder). More comprehensive details about the functional motor task methodology can be found in our recent methodological paper (see Figure 5 in 42).

2.2 Upper-limb function

All participants performed the two functional UL tasks, as detailed in earlier studies (24,42).

2.2.1 Paced reaching task

Participants were seated on a chair fitted with armrests and were instructed to reach a target (a table tennis ball) placed in front of them at a height of 80 cm and a distance which facilitated the complete extension of the arm. A Kinect sensor (V2, Microsoft, USA), sampled at 30 Hz, was positioned 1.70 m above and 1.60 m away from the target. Participants performed five movements per 20-second block, timed to vocal prompts ("go"; "stop"). After a familiarization block with each arm, participants completed three blocks using their non-dominant/paretic hand, followed by three blocks using their dominant/non-paretic hand. Each block was interspersed with 20 seconds of rest. Then, participants repeated the task for three blocks with each hand under a movement-constrained condition, wherein their shoulders were immobilized to minimize trunk movements.

2.2.2 Circular steering task

This task was based on the speed-accuracy trade-off (43). Participants were seated on a chair in front of a horizontal graphic tablet (A3 size; Wacom, Kazo, Japan) equipped with a stylus affixed to a mouse pad, facing a 24-inch vertical screen projecting a circular target (33-inch circumference) with a 2 cm tunnel. A Kinect was placed above the graphic tablet at the height of 1.70 m. The task was delivered using a lab-made software, the LSL-Mouse (https://github.com/KarimaBak/LSL-Mouse). Participants were instructed to move a cursor as fast as possible in a clockwise direction. During the familiarization phase, participants were instructed to accelerate if errors (any instances outside the 2 cm circular tunnel boundaries) were below 15% (based on pilot testing). The task comprised three blocks for each arm (20 seconds of task with 20 seconds of rest), commencing with their non-dominant/paretic hand.

2.2.3 Clinical assessments of paretic upper limb impairment

In conjunction with the functional kinematics and brain evaluation, patients' UL motor function was appraised through clinical evaluations. We utilized several recognized and validated tests, including the FM-UE (36,41), the Box and Block test (BBT; 44), the Wolf-motor function test (WMFT, 45), the Barthel

Index (BI, 46), and the Proximal-arm non-use test (PANU, 3,4). Comprehensive details of these evaluations are described in the cited references.

The FM-UE assesses upper limb motor impairment, while the BBT measures arm and hand grasping function. WMFT evaluates upper limb function, and the BI measures overall functional recovery (independent function in activities of daily living). The PANU test measures the degree to which the paretic upper limb, specifically movements at the shoulder and elbow, is not spontaneously used. These tests collectively provide a comprehensive overview of the paretic UL's functional capacity and impairment (for the FM-UE) level in stroke patients.

Brain activity (fNIRS and fEEG)

Participants wore a custom neoprene head cap equipped with a combined fEEG-fNIRS system to monitor brain activity within the left and right sensorimotor cortical regions during both functional motor tasks. We utilized a wireless Starstim fNIRS integration system (Starstim8, Neuroelectrics, Barcelona, Spain; Octamon+, Artinis Medical Systems, Elst, The Netherlands) to measure fEEG and fNIRS signals. Details regarding the placement of the 16 channels, comprising four fNIRS and four fEEG channels per SM1 hemisphere, are outlined in a previous article (see Figure 1 in 24).

The fEEG electrodes were positioned in and around SM1 cortices: C4, FC2, FC6, CP2 in the right hemisphere and C3, FC1, FC3, CP1 in the left hemisphere, in alignment with the international 10–10 system. The electrodes (NG Geltrode, Neuroelectrics, Spain) were filled with electro-gel (Signa Gel®). Using an ear clip, reference electrodes (CMS, DRL) were placed over the right earlobe. The fEEG signals were sampled at a rate of 500 Hz. We controlled the wifi- fEEG device via a software interface (Neuroelectrics Instrument Controller, NIC v 2.0).

For the fNIRS recording, we used a continuous-wave system employing two wavelengths to capture changes in HbO_2 and HbR overlying the left and right SM1, sampling at 10 Hz. The two receivers were positioned at the C1 and C2 locations of the 10–10 fEEG system, with four transmitters placed 3 cm from the receivers using plastic holders. The fNIRS Bluetooth device was managed through a software interface (Oxysoft, v3.2.51.4, Artinis Medical Systems, Elst, The Netherlands).

Following the equipment setup, participants were asked to perform a wrist extension task to verify if the movement induced a hemodynamic response.

2.4 Data analysis

2.4.1 Task performance

The paced reaching and circular steering task kinematics analysis was done based on previous work (3,4,47) and LSL-Kinect software (LSL-KinectV2: https://github.com/KarimaBak/LSL-KinectV2). For the paced reaching task, we calculated the proximal-arm non-use (%) and the hand mean velocity (mm/s). For both tasks, we calculated as trunk compensation parameter, the range of trunk anterior flexion (°)

representing the use of the trunk to realize the reaching movement. And, we calculated, as arm use parameters the range of elbow extension (°) representing the use of whole arm to perform the movement.

We assessed the speed-accuracy trade-off during the circular steering task using the Index of Performance (IP_e in bits/s, 48). We calculated the Index of Effective Task Difficulty (ID_e) with the formula: $ID_e = \frac{2\pi R}{W_e}$, where R represents the subject's mean circular path radius, and We denotes the effective path width. We determined W_e using MacKenzie's formula (49): $W_e = \sqrt{2\pi e} * \sigma$, where σ is the standard deviation of the radius. We then computed IP_e by dividing ID_e by the movement time (MT). In addition, we calculated the speed as laps per second and accuracy as bias (W_e/W, following 49) of the movement.

2.4.2 Brain activity (fNIRS and fEEG*)*

We processed all fNIRS raw data using the HOMER toolbox in MATLAB (Homer2 NIRS processing package, 50) with the files generated by the Lab Recorder (xdf files). Pre- and post-processing steps are detailed in a previous study (24). We used the relative changes (Δ) in peak HbO_2 concentration as an indicator of brain activity.

We analysed all fEEG data using the EEGLAB toolbox on MATLAB (51, version 2021.1), with the files generated by the Lab Recorder (xdf files). Details of pre- and post-processing steps are provided in a previous study (24). We calculated the event-related spectral perturbations (ERSP) in the alpha (8-13 Hz) and beta (14-29 Hz) rhythms, revealing average power changes in these specific time frequencies. This information provides insight into event-related desynchronization (ERD; power decrease in a specific frequency band relative to baseline, i.e., rest) and synchronization (ERS; power increase in a specific frequency band relative to the task). For fEEG and fNIRS analyses, parameters were averaged by tasks (paced reaching; circular steering), hand condition (dominant / non-paretic; non-dominant / paretic), and hemisphere (contralateral / ipsilesional ; ipsilateral / contralesional).

2.5 Statistical analyses

Statistical analyses were performed using R software (version 4.2.1) and the ggplot2 (52), dplyr (53) and rstatix (54) packages. Parametric tests were employed following the validation of data normality via the Shapiro-Wilk test and visual examination of Q-Q plots. Effects sizes were indicated using the partial eta square (η^2p), with small (0.02), medium (0.13), and large (0.26) effect sizes noted (55,56) . A threshold of $p < .05$ was used for statistical significance. If necessary, pairwise comparisons were conducted using t-tests, with the Benjamini-Hochberg procedure applied for p-value correction in multiple tests (57). Significant effects were interpreted only when of sufficient intensity ($\eta^2p > .02$). All values are presented as mean (SD) unless stated otherwise. In the absence of three-level interaction effects, only two-level interaction effects were reported for each factor combination. Note that the degrees of freedom of the analysis are varied across variables due to differing exclusion rates for subjects.

Tasks performance and kinematics

The movement parameters for the circular steering task (IPe, speed, accuracy, range of trunk anterior flexion, range of elbow extension) were evaluated through a mixed ANOVA, which included group (healthy and stroke) as a between-subject factor, and hand (non-paretic/dominant and paretic/non-dominant hand) as a within-subject factor. Similarly, a mixed ANOVA was employed for the paced-reaching task (PANU, mean velocity, range of trunk anterior flexion, range of elbow extension), incorporating group (healthy and stroke) as a between-subject factor and hand (non-paretic/dominant and paretic/non-dominant hand) and condition (spontaneous- SAU and maximal- MAU) as within-subject factors.

Cortical activations

For the analysis of fNIRS peak of ΔHbO_2 and fEEG Alpha and Beta ESRPs, a mixed ANOVA was applied with group (healthy and stroke) as a between-subject factor, and hand (non-paretic / dominant and paretic / non-dominant hand), condition (spontaneous- SAU and maximal- MAU, paced-reaching task), and hemisphere (contralateral / ipsilesional ; ipsilateral / contralesional) as within-subject factors.

Brain-movement relationship

In our investigation of the association between performance in the circular steering task and brain activation (fNIRS peak ΔHbO_2) across the groups, we consistently applied Spearman rank correlation analysis. This approach was chosen to account for the non-normal distribution of some variables and to maintain consistency across the analysis, thus enhancing comparability of our findings. We choose to keep only moderate effects to avoid false effects, thus, we just present correlation with at least a $p < .01$ and a $r_s^2 > .25$. Only those effects were reported to facilitate the results presentation.

3. Results

3.1 Tasks performance and kinematics

Circular steering task

On the circular steering task (Fig. 1), we found a higher performance (IP_e) in the healthy group and with the dominant hand / non paretic hand for both groups (Group: $F_{(1,40)} = 20.52$, $p = .000$, $\eta^2_p = .34$; Hand: $F_{(1,40)} = 53.00$, $p = .000$, $\eta^2_p = .57$) with no Group × Hand interaction ($F_{(1,40)} = 1.97$, $p = .169$, $\eta^2_p = .05$). For the speed component (i.e., time per lap), we found a Group x Hand interaction ($F_{(1,40)} = 5.83$, $p = .020$, $\eta^2_p = .13$). Post-hoc analysis showed that the time per lap difference between paretic/non-dominant and non-paretic/dominant hand, was significantly higher for the stroke group, with a longer time per lap with the paretic arm (Healthy: $\eta^2_p = .25$; Stroke: $\eta^2_p = .34$). Moreover, it shows that the time per lap was significantly shorter in the healthy group, whatever the hand. For the accuracy component (i.e., bias), we did not find any significant effects (healthy / dominant: bias 183 (± 56.6); healthy / non-dominant: bias = 189 (± 49.5); stroke / non-paretic: bias = 202 (± 77.9); stroke / paretic: bias = 233 (± 96.3).

On the circular steering task, we found that the trunk compensations were higher in the stroke group when performing with the paretic hand (Group x Hand interaction: $F_{(1,35)} = 8.95$, $p = .005$, $\eta^2_p = .20$). For both groups, the range of elbow extension was significantly higher with the dominant / non -paretic hand ($F_{(1,35)} = 8.28$, $p = .007$, $\eta^2_p = .19$).

Paced reaching task

On the paced reaching task (see Figure 2), we found a Group x Hand interaction on the PANU, range of trunk flexion and hand mean velocity (PANU: $F_{(1,37)} = 8.85$, $p = .005$, $\eta^2_p = .19$; range of trunk flexion: $F_{(1,37)} = 5.01$, $p = .031$, $\eta^2_p = .12$; hand mean velocity: $F_{(1,37)} = 4.93$, $p = .033$, $\eta^2_p = .12$). The range of trunk anterior flexion, and PANU were higher for the stroke paretic hand and at the same time the hand mean velocity was lower. For the range of trunk anterior flexion, we found a Hand x Condition interaction showing that the range of anterior trunk flexion was lower in the maximal condition for the non-dominant / paretic hand ($F_{(1,37)} = 4.88$, $p = .033$, $\eta^2_p = .12$). We also found a condition effect on the range of elbow extension, for both groups, it was higher in the maximal condition ($F_{(1,37)} = 7.11$, $p = .011$, $\eta^2_p = .16$).

3.2. Brain activity

Brain activity (fNIRS: peak of ΔHbO_2; fEEG: ERD and ERS) during paced reaching and circular steering tasks are presented in Figure 3 (fNIRS) and Figure 4 (fEEG) and the statistical results are detailed in supplementary materials for group, hand, hemisphere, and condition effects and two-level interaction effects with each factor combinations (see Supplementary material files 1 and 2). The significant three-levels interactions are reported in the text.

3.2.1 fEEG

Circular steering

The analysis of the mean ΔHbO_2 peak during the circular steering task showed no significant effects.

Paced reaching task

The analysis of the mean ΔHbO_2 peak during the paced reaching task showed a higher activation for stroke group with the paretic hand (Group x Hand: $F_{(1,36)} = 4.51$, $p = .041$, $\eta^2_p = .11$) and a higher activation in the contralateral side compared to the ipsilateral one for both groups (Hemisphere: $F_{(1,36)} = 6.45$, $p = .016$, $\eta^2_p = .15$). Nevertheless, the 3-way interaction Group x Hand x Hemisphere ($F_{(1,36)} = 2.82$, $p = .102$, $\eta^2 p = .07$) showed a trend for the stroke group paretic hand, where there seems to be no difference between the two hemispheres or the ipsilateral (contralesional) hemisphere being higher than the contralateral (ipsilesional) side.

3.2.2 fEEG

Circular steering task

On the circular steering task (Figure 4A), we found for Beta ERS a 3-way interaction Group x Hand x Hemisphere ($F_{(1,25)} = 5.02$, $p = .034$, $\eta^2_p = .17$). Post-hoc comparisons revealed that, for the stroke group, there was a Hand x Hemisphere interaction ($F_{(1,14)} = 7.56$, $p = .016$, $\eta^2_p = .35$) showing a lower post-movement synchronization in the contralateral (ipsilesional) hemisphere when performing with the paretic hand (see figure 4A). The analysis of the mean ERSP did not show any main or interaction effect of Group on Alpha and Beta ERD nor Alpha ERS.

Paced reaching task

On the paced reaching task, there was a Group x Brain interaction for the Beta ERD ($F_{(1,23)} = 4.98$, $p = .036$, $\eta^2_p = .19$). Although there was a tendency to a Group effect ($F_{(1,29)} = 3.88$, $p = .051$, $\eta^2_p = .03$) showing a smaller Beta desynchronization in the stroke group (Figure 4B), the post-hoc comparisons between the different modalities of the Group x Brain interaction were too low to emerge, and thus are not shown in Figure 4B. For the Alpha ERD we did not find any significant main or interaction effect. For the Beta ERS, we found a Hand x Condition interaction showing that for the stroke group, the post-movement Beta synchronization was higher for the maximal condition ($F_{(1,21)} = 8.80$, $p = .007$, $\eta^2_p = .30$; see Figure 4C). We also found a 3-way interaction between Group x Hand x Hemisphere ($F_{(1,21)} = 5.08$, $p = .035$, $\eta^2_p = .20$). Post-hoc comparison revealed a Hand x Brain interaction for the stroke group ($F_{(1,27)} = 14.9$, $p = .001$, $\eta^2_p = .36$) showing a higher Beta ERS with the dominant / non-paretic hand in the stroke group. For Alpha ERS, we found a Group x Hemisphere interaction ($F_{(1,16)} = 4.53$, $p = .049$, $\eta^2_p = .22$). Post-hoc comparisons revealed that there was a Group effect in the ipsilateral hemisphere ($F_{(1,53)} = 28.8$, $p = .000$, $\eta^2_p = .35$), showing a higher post-movement Alpha synchronization in the ipsilateral hemisphere of the stroke group in comparison to the healthy group (see Figure 4D). There was also a Hand x Hemisphere interaction ($F_{(1,16)} = 6.28$, $p = .023$, $\eta^2_p = .28$). Post-hoc comparisons revealed a Hand effect in the contralateral hemisphere ($F_{(1,51)} = 4.70$, $p = .035$, $\eta^2_p = .08$), with a higher post-movement synchronization in the non-dominant / paretic hand.

3.3 Brain-movement-clinical scores relationship in the Stroke group

3.3.1 Brain-movement relationship

Circular Steering task

The spearman rank correlation analysis for the circular steering task with paretic hand showed that an increased use of the trunk was associated with a higher movement Beta desynchronization on the contralateral (ipsilesional) hemisphere ($p = .007$, $r_s^2 = .44$) and a tendency in the ipsilateral (contralesional) side ($p = .080$, $r_s^2 = .19$, see Figure 5A). We also found that for a higher IP_e and time per lap in the circular steering task, there was a higher post-movement Beta synchronization in the ipsilateral (contralesional) hemisphere and a tendency in the contralateral one (IP_e - Ipsilateral: $p = .000$, $r_s^2 = .69$; Contralateral: $p = .050$, $r_s^2 = .24$; Time per lap – Ipsilateral: $p = .000$, $r_s^2 = .49$; Contralateral: $p = .031$, $r_s^2 = .28$, see Figure 5B).

Paced reaching task

When reaching in the maximal condition, we found that elbow extension was negatively correlated with the ipsilateral (contralesional) peak of ΔHbO_2 ($p = .008$; $r_s^2 = .32$, see figure 6). We also found that the slower to do the maximal reaching have a higher post-movement synchronization in the ipsilateral hemisphere ($p = .003$, $r_s^2 = .47$, see Figure 6A). We found that for a higher spontaneous elbow extension the Beta post-movement synchronisation was higher in both hemispheres (Ipsilateral: $p = .001$, $R^2 = .50$; Contralateral: $p = .000$, $r_s^2 = .62$). On the same conditions, the Alpha post-movement synchronization in the ipsilateral hemisphere was also positively correlated to elbow extension ($p = .009$, $r_s^2 = .37$).

3.3.2 Brain-clinical scores relationship

For the correlation between the brain parameters and the clinical scores, we found that a more marked Alpha ERD on the circular steering task was associated to a lower FM-UE (Paretic hand - Ipsilateral: $p = .000$, $r_s^2 = .62$; Paretic hand – Contralateral: $p = .000$, $r_s^2 = .55$; Non-paretic hand - Ipsilateral: $p = .003$, $r_s^2 = .43$; Non-paretic hand – Contralateral: $p = .006$, $r_s^2 = .40$, see Figure 7A).

For the maximal condition of the reaching task with the paretic hand, we found a negative correlation between the peak of ΔHbO_2 and FM-UE, showing that for a better clinical score there was a lower ipsilateral (contralesional; $p = .003$, $r_s^2 = .37$) and contralateral (ipsilesional: $p = .033$, $r_s^2 = .23$) peak of ΔHbO_2 (see Figure 7B).

4. Discussion

This study investigated the impact of chronic stroke on the bilateral SM1 electrical (fEEG) and hemodynamic (fNIRS) responses during unilateral proximal UL movements. We concurrently recorded bilateral SM1 activity via combined fNIRS/ fEEG, along with UL movements using kinematic tracking. Two previously established UL functional tasks were employed: a paced-reaching task and a circular steering task designed to interrogate the speed-accuracy trade-off (3,24). Our main finding was a greater increase in bilateral SM1 activity (fNIRS-peak ΔHbO2) for the paretic than non-paretic UL during the paced-reaching task. Furthermore, during the circular steering task, fEEG and kinematic analyses disclosed that enhanced trunk flexion was linked to greater desynchronization in fEEG Beta band power, and a higher performance (IP_e) was associated to higher post-movement Beta synchronization. We also found that greater use of elbow extension was associated to a lower fNIRS SM1 activity and, to higher post-movement fEEG Beta synchronization. Regarding the movement modifications, we observed that stroke patients showed slower speeds, increased trunk compensation, and decreased active use of the elbow-shoulder joint, particularly on the paretic side.

For the paced-reaching task, a greater increase in bilateral SM1 activation was detected with fNIRS during the movement with the paretic hand which tended to coincide with reduced fEEG Beta desynchronization at the onset of movement. These results might indicate compensatory brain mechanisms designed to mitigate the effects of stroke on movement execution. The fEEG findings presented a lower SM1 excitability in the stroke group, which was associated to an increased activation of the fNIRS SM1 when moving the paretic hand. This aligns with previous studies suggesting reduced brain asymmetry and increased activity as potential mechanisms of post-stroke motor recovery (58,59). These findings can also be compared to the study by (11) which analysed fNIRS activity during a modified Box & Block forward reaching test in stroke patients compared to a healthy cohort. Despite the inferior performance, stroke patients demonstrated increased lesioned hemisphere activity during paretic arm reaching.

For the circular steering task, our findings indicated a reduced performance in the stroke group, while task-related fNIRS peak and fEEG-ERD remained comparable across both groups. This task relies heavily on visuomotor control: continuous monitoring and rectification of the trajectory while moving as fast as possible, embodying the concept of the continuous speed-accuracy trade-off (60). Given these extensive requirements on sensorimotor control networks, this task is a good measure of neural efficiency, i.e., the amount of neural resources required to execute a given task (61). In this context, the hypothesis of neural efficiency postulates that individuals with higher cognitive ability exhibit lower energy consumption in the brain for equivalent tasks (62). Given the decreased performance in the stroke cohort and similar brain activity levels, it could be inferred that these individuals exhibit reduced neural efficiency when performing the circular steering task. However, as our study was confined to the SM1 region, we cannot draw a definitive conclusion regarding overall neural efficiency. Indeed, the circular steering task demands a significant level of visuomotor control, and previous research has suggested that the prefrontal area plays a substantial role in controlling such movements (63). However, despite the potential impairment of neural efficiency in SM1, the absence of significant brain modification in stroke patients may be explained by considering the task's nature. Indeed, the task required maximal performance from the healthy subjects as well. Moreover, our previous study found no effects of healthy aging on the level of fNIRS SM1 activity in this task, as old adults engaging both hemispheres to compensate for their reduced neural efficiency (24). We can thus hypothesize that when performance is maximized ("as fast and precise as possible") for all participants, brain activity will reach its maximum, and compensatory mechanisms may rely on alternative neural pathways, such as the prefrontal areas (63). Our previous work also indicated no significant effects of healthy aging on any brain or kinematics parameters during the reaching task. This lack of effect underscores the notion that, the reaching task was, for our healthy adults, considerably simpler and less demanding than the circular steering task. However, in the present study, we observed modifications in brain activity during the paced-reaching task, potentially due to its complexity for post-stroke patients demonstrating motor compensation to complete the task successfully as in the circular steering task.

Focusing on the stroke-induced alterations in movement, we observed the deployment of compensatory strategies by stroke patients to accomplish both functional tasks using their paretic UL. Specifically, in the circular steering task, stroke patients employed their trunk to facilitate task completion with their paretic hand, concomitantly showing reduced use of the elbow-shoulder joints. Similarly, during the reaching task, we detected evidence of proximal-arm non-use (i.e., non-mandatory trunk compensation) when the task was performed with the paretic hand. Additionally, the velocity of the paretic hand was reduced, a finding of particular interest given our use of paced reaching, indicating that the stroke patients were moving slowly to follow the paced rhythm. This result could be explained by the existence of strong correlations between clinical scores and velocity implying that the patients' movement difficulties may be attributed to their level of impairment. This observation is consistent with prior studies demonstrating that the speed of the paretic movement is slower than that of the non-paretic movement (64). This also aligns with our findings from the circular steering task, indicating reduced movement speed in the stroke group, particularly for the paretic arm.

Exploring the connection between brain modifications and kinematic compensations, we identified an association between trunk use and fEEG Alpha desynchronization in the circular steering task. This could imply that trunk use necessitates mobilizing increased neuronal resources across both hemispheres. Further, we detected alterations in post-movement Beta synchronization associated with motor performance. Specifically, a higher IP_e correlated with increased ERS. We could hypothesize that, in this task, the high demand level is sustained by the highest-performing subjects, who are also likely to move fastest. It is well established that increased speed correlates with higher neural activity (65), implying that the ratio between the movement and rest period could be higher. Regarding the reaching task, we observed different effects depending on whether the task was performed spontaneously or maximally. In the spontaneous reaching task, our findings mirror those of the circular task, with higher post-movement synchronization observed in better performers. Conversely, the positive correlation between movement time and Alpha ERS in the maximal condition is more challenging to explain. One could hypothesize that the enhanced synchronization for slower performers might be explained by the extended duration of neural demand they experience during the task. As they move slower, their SM1 will be engaged for a longer time (i.e., the paced reaching task typically entails 2 seconds of movement and 2 seconds of rest), leading to higher synchronization in the ERSP. Nevertheless, the negative correlation between fNIRS brain activity and elbow extension could be akin to the circular steering task, could suggest an over-activation in lower performers who engage their trunk to facilitate movement. Another hypothesis could be that in the maximal condition, we instruct patients to use their elbow-shoulder joints maximally. Consequently, those who employ these joints less frequently will likely require more resources and increased brain activity. Thus, we could observe either the effect of trunk use or the effect of effort. However, our measurements cannot discern which hypothesis is closer to the truth (i.e., a measure of perceived effort could have been beneficial).

Lastly, an exploratory aim of this study was to investigate the association between stroke patients' clinical scores and the corresponding brain parameters. We observed meaningful correlations that underscore the potential of fNIRS and fEEG methodologies in the context of stroke rehabilitation (11,66,67). First, we found that a more pronounced Beta desynchronization at movement was linked to a lower score on the FM-UE. It is in line with prior research illustrating that a more significant event-related desynchronization in the sensorimotor cortex correlates with an enhanced demand for concentration and excitatory drive of pyramidal cells during task execution (68). For example, studies on grip tasks during rehabilitation have shown that with progression and motor improvement, there is a reduced requirement for cortical engagement and effort to perform the grip task (69). Secondly, the inverse correlation between fNIRS brain activity and FM-UE indicates that a lower clinical score corresponds with an increased SM1 activation during the execution of the paced-reaching task. This is plausible considering the kinematics of the task. Indeed, we found an association between higher elbow extension and higher WMFT scores (data not shown). Which could suggest that patients who utilize their arm extension more during the reaching task will have higher clinical scores, and reversely for patients using more trunk compensation to do the task. It is also known that elbow extension negatively correlates with trunk compensation (3,47). Consequently, patients with greater upper limb deficits may rely more on their trunk to reach the target, leading to larger brain activity in response to the increased demand for the trunk.

This study has several limitations. First, age and gender matching were not strictly adhered to, with a more balanced male/female ratio in the healthy group, which was also older than the stroke group (mean age for healthy group = 72 yrs., stroke group = 64 yrs.; male/female ratio for healthy group = 11 women; stroke group = 8 women). Additionally, in this study we did not take into account the role of associated cognitive disorders (in particular visuospatial disorders, for example, which certainly interfere a great deal with the circular task) and sensory disorders (also very important for the circular task, which relies heavily on proprioception), as well as spasticity, which interferes a great deal with elbow extension and compensatory movements by the trunk. Lastly, the reaching task, paced at a consistent rhythm for all participants, could present a significant limitation. This speed constraint could lead to an augmented use of compensatory movements in stroke patients to reach the ball at the required speed (70).

5. Conclusion

In conclusion, this study provides insight into the impacts of stroke on the task-related brain activity and kinematics during unilateral upper limb movements that engage full UL joint movements (i.e., shoulder, elbow, wrist). Our findings highlight the brain and movement compensations associated with a chronic post-stroke population. Additionally, we demonstrate the utility of a combined fNIRS-fEEG recording approach, which correlates with kinematic and clinical scores. The concurrent evaluation of brain and kinematic parameters offers complementary information about the execution of paretic movements, allowing for extracting specific components for targeted intervention during rehabilitation. Moreover, these measures can enrich routine clinical assessments in ecological settings. As perspectives, the ReArm project, of which this study is a part, aims to discern the effects of rehabilitation on these specific brain and kinematic parameters. Furthermore, we aim to investigate their applicability in routine evaluation to facilitate more personalized rehabilitation strategies.

Abbreviations

BBT	a Box and Block Test
BI	Barthel Index
ERD	Event Related Desynchronization
ERS	Event Related Synchronization
ERSP	Event Related Spectral Perturbation
FM-UE	Fugl-Meyer Upper-Extremity
ID_e	Index of Task Effective Difficulty
IP_e	Index of effective performance
fEEG	Functional Electroencephalography
fNIRS	Functional Near-infrared Spectroscopy
HbO_2	Oxygenated blood
HbR	Deoxygenated blood
MAU	Maximal Arm Use
PANU	Proximal Arm Non-Use
SAU	Spontaneous Arm Use
SD	Standard Deviation
SM1	Primary Sensorimotor cortex
WMFT	Wolf Motor Function Test

Declarations

Authors contribution

K.B. coordinated the project and obtained the funding. C.O.M. and G.F. wrote the original draft. C.O.M. acquired the data. C.O.M. and G.F. analyzed the data. C.O.M., G.F., M.M., K.B., D.M., I.L. and S.P. participated in the conceptualization of this project and in the interpretation of the data. G.D., B.X., M.M., S.P., K.B. and C.O.M. developed the experimental set-up and analysis solution for the fNIRS-fEEG signals. D.M., M.M., K.B. and G.F. developed the experimental set-up and analysis solution for the kinematics signals. M.M., D.M., S.P., I.L., M.D., J.F., B.X., G.D. and K.B. participated in the reviewing and editing of the manuscript. All authors read and approved the final manuscript.

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Data availability

Data will be available from the corresponding author on reasonable request.

Declaration of Competing Interest

The authors have no conflict of interest to declare.

Consent for publication

All authors give their consent to publish.

Ethics approval and consent to participate

This study was conducted in the framework of ReArm project, and the French Research Ethics Committee (Comité de Protection des Personnes- CPP SUD-EST II) approved the study protocol (No. ID-RCB 2019-A00506-51) for the stroke patient’s inclusions. And the the local Ethics Committee of the EuroMov DHM laboratory approved it for the healthy subjects (EuroMov IRB, number 1912B). Before participation, all participants provided written informed consent.

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Figures

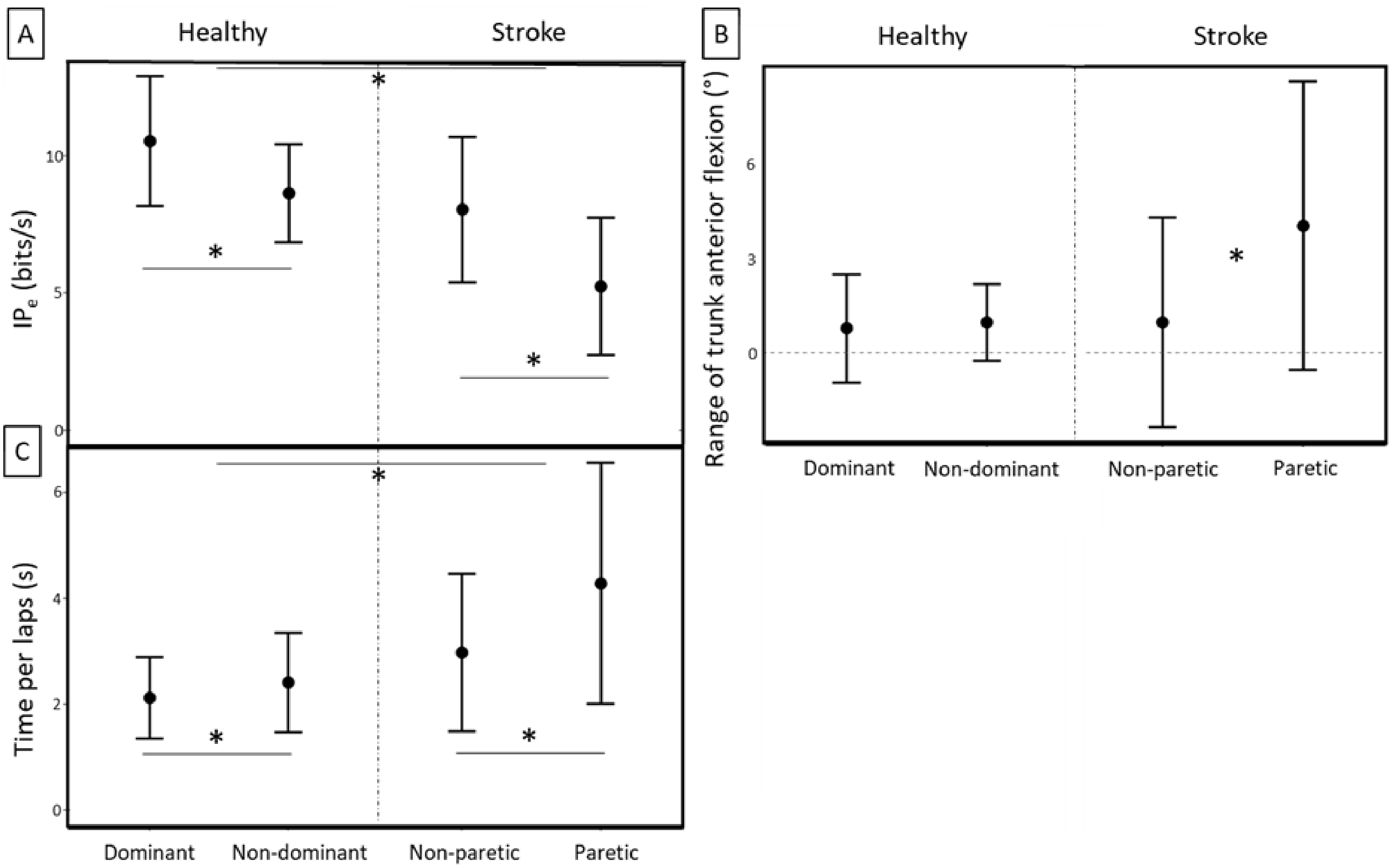

Figure 1

Circular steering task performances and strategies *(mean ± SD)* for the two groups and according to hand trial. A) Index of performance (IP_e); B) Range of trunk anterior flexion; and C) Time per lap. (* for statistically significant differences at $p < .05$).

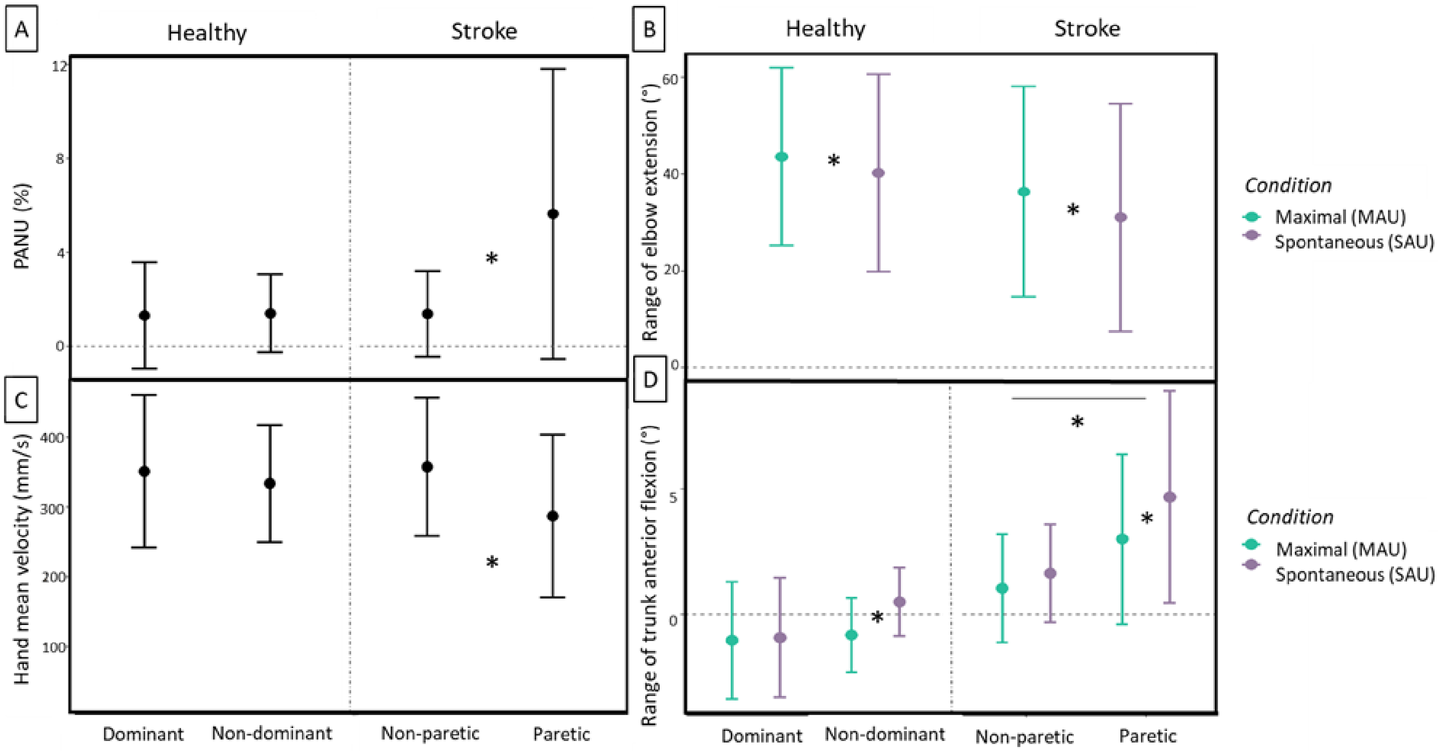

Figure 2

Paced reaching task upper limb movement strategies *(mean ± SD)* for the healthy and stroke groups and according to hand trial and condition (for condition interaction and/or effects). A) Proximal-arm non-use, PANU; B) Range of elbow extension; C) Hand mean velocity; and D) Range of trunk anterior flexion. (* for statistically significant differences at p < .05).

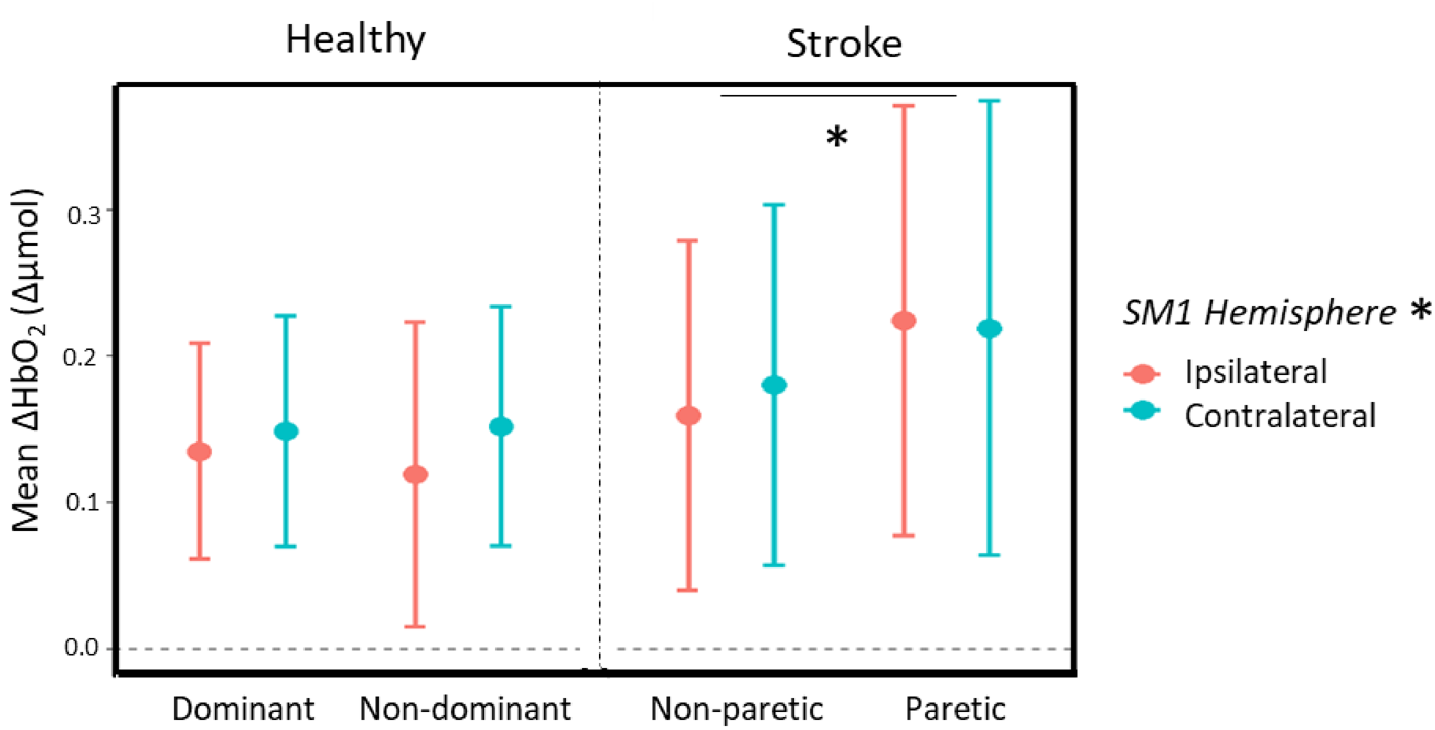

Figure 3

Paced reaching task fNIRS mean ΔHbO_2 peak (mean ± SD) for the healthy and stroke groups as a function of hand and hemisphere (ipsilateral in orange; contralateral in cyan). * For statistically significant differences at $p < .05$: hand effect in the stroke group and hemisphere effect for all groups and conditions.

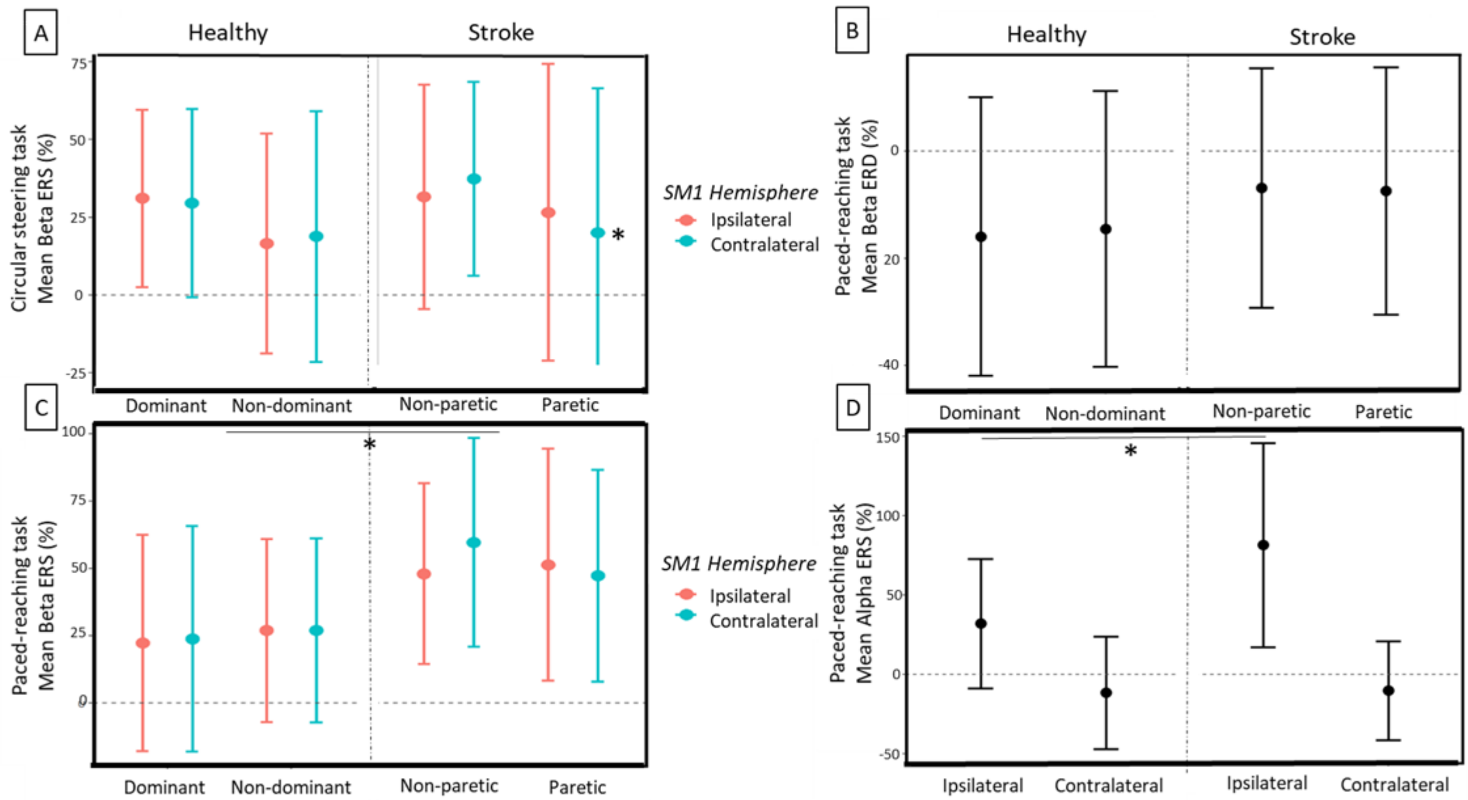

Figure 4

fEEG Beta event-related spectral perturbation (ERSP) *(mean ± SD)* for the healthy and stroke groups. Circular steering task*:* lower Beta event-related synchronization (ERS) in contralateral (ipsilesional) hemisphere of the stroke group after paretic arm movement (A). Paced reaching task: Beta event-reated desynchronisation (ERD) with a tendency to lower ERD in the stroke group (B), higher Beta ERS in the stroke group for both hemispheres (C), and a higher Alpha ERS for the stroke group in the Ipsilateral hemisphere. (* for statistically significant differences at $p < .05$)

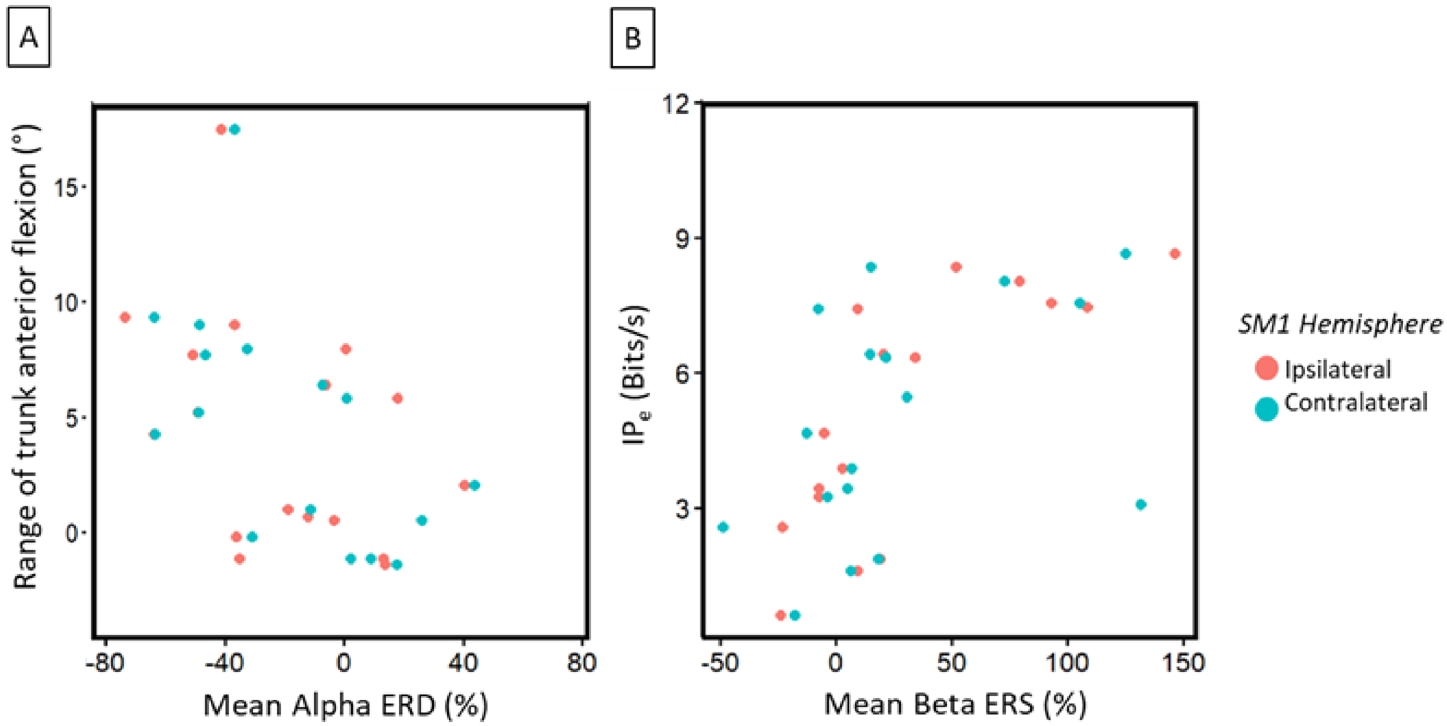

Figure 5

Stroke group correlation between A) Alpha ERD and the trunk use, and B) Beta ERS and the index of effective performance (IP_e) during the circular steering task with the paretic arm.

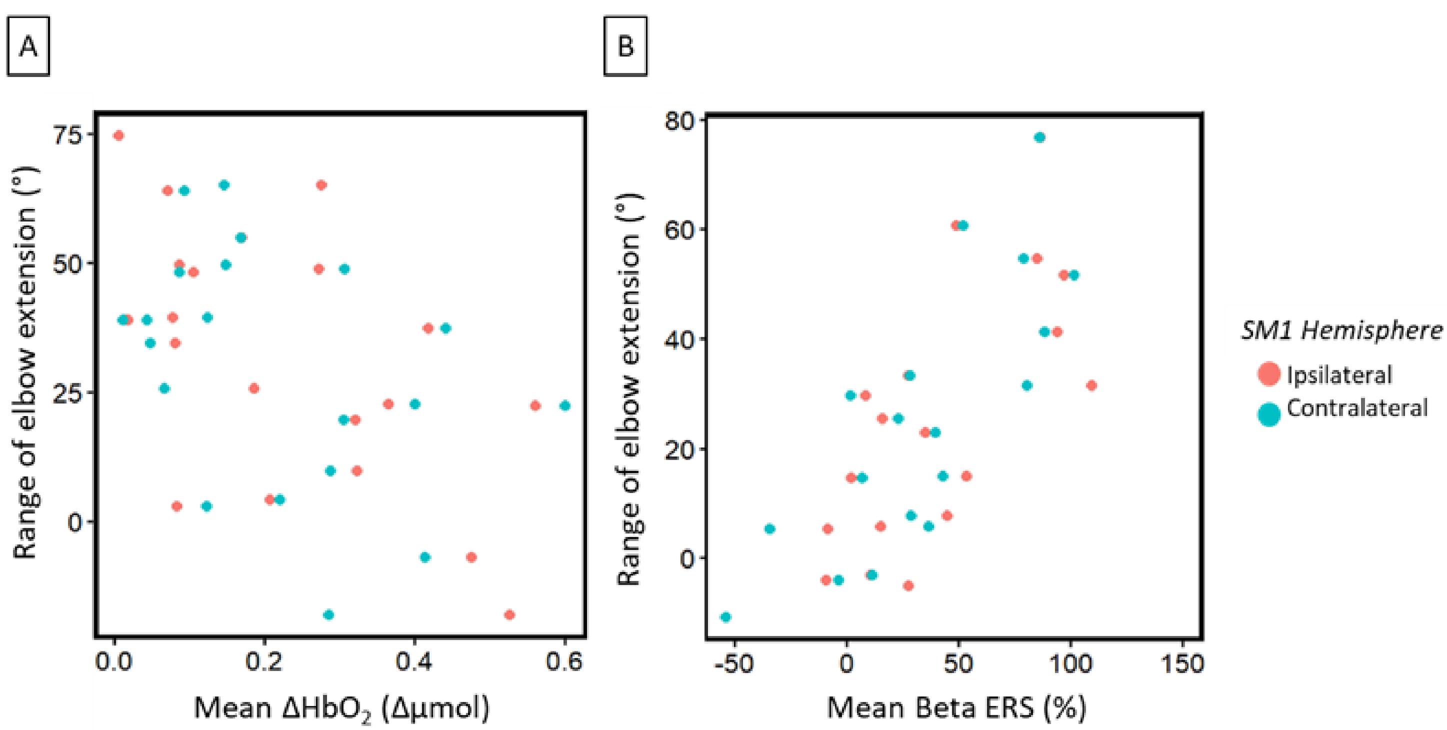

Figure 6

Stroke group correlation between A) Peak of ΔHbO_2 and elbow extension and B) Mean Beta ERS and elbow extension during the paced-reaching task with the paretic arm.

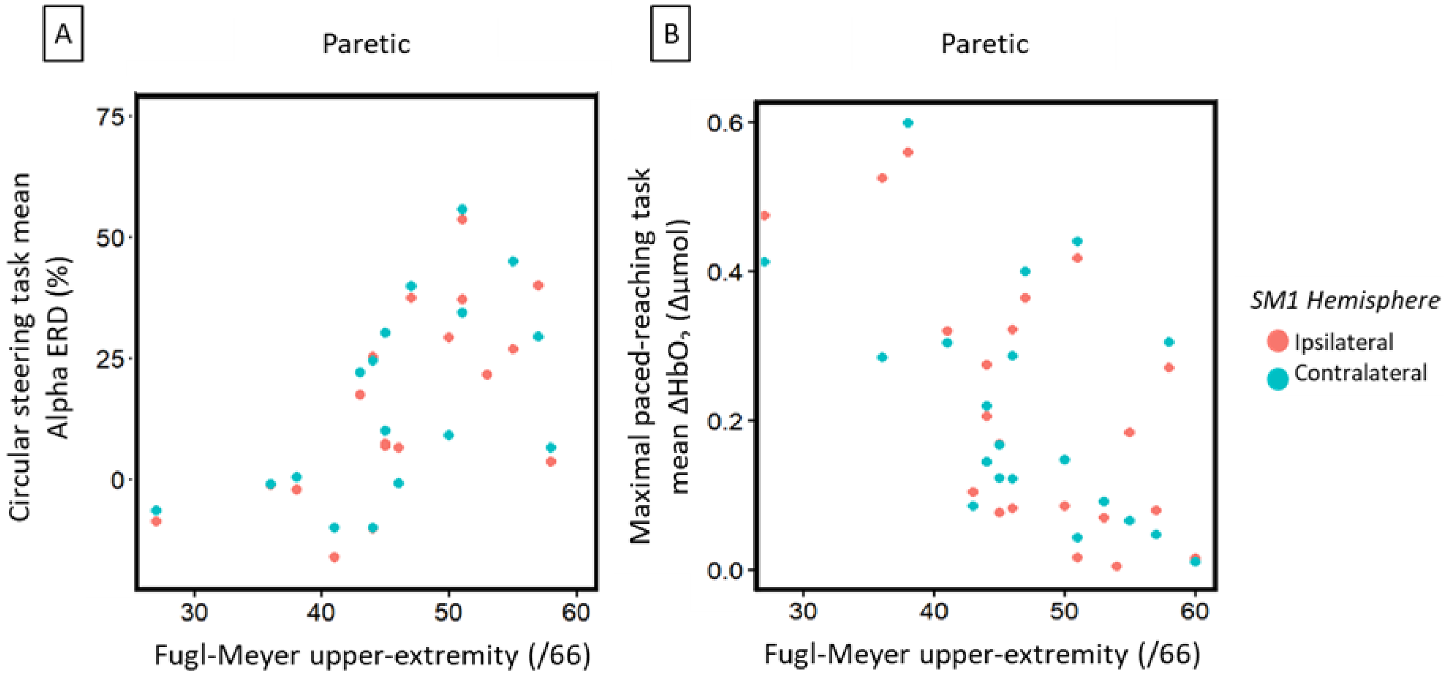

Figure 7

Stroke group correlation between A) Alpha ERD during the circular steering task and the FM-UE test and, B) Peak of ΔHbO_2 during the maximal paced-reaching task and the FM-UE test.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryMaterialsFile1File2.docx