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Alteration of Cortical Somatosensory Feedback in Post-Stroke Movement Control

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***Abstract*—Sensory feedback is of vital importance in motor control, yet is rarely studied in diseases which frequently result in motor deficiency, such as hemiparetic stroke. This study employs the laterality index (LI) of somatosensory evoked potentials (SEPs) to investigate whether sensory feedback is altered in hemiparetic stroke during movements of the paretic arm, with a hemispheric shift from the lesioned hemisphere toward contralesional hemisphere. Through experimental design involving the isometric lifting of the paretic arms during tactile finger stimulation and the analysis of LI in SEPs P50 and N100, we found: 1) increased contralesional sensory activity in stroke participants when they are receiving sensory input in their paretic hand for both P50 and N100 and 2) the contralesional N100 activity is enhanced when stroke participants are performing an isometric arm lifting task. These results indicate a time-dependent shifting of sensory feedback from the sensorimotor areas in the lesioned side to the contralesional side of the stroke brain.**

I. INTRODUCTION

The sensorimotor system in the brain is an integrated system where the sensory and motor circuits interact with each other during movement control. The sensorimotor system can undergo reorganization following an injury to the brain, during the recovery process. Previous studies focused on the pathological motor control in hemiparetic stroke have revealed functional and structural changes to motor pathways from the brain to the muscles, showing an increased reliance on contralesional cortico–bulbospinal pathways (which is ipsilateral to the paretic limb) [1]–[5]. However, it is unknown whether a similar hemispheric shift occurs in the sensory system to adapt to this motor pathway change and how sensory feedback would shift to the contralesional hemisphere to support such the use of contralesional motor pathways in hemiparetic stroke [1], [2], [6]. Recent studies in our group have shown increased recruitment of contralesional sensory cortical regions when stroke participants were passively receiving tactile stimulations to their fingers of the paretic arm [7], [8]. Similarly, enhanced resting-state interhemispheric connectivity of the primary sensory cortex has been previously reported to be associated with motor impairment after stroke [9]. Since no movement task was involved in these previous studies (either only passively receiving sensory input or at rest), it is still not clear whether the reported increase of sensory cortical activity at the contralesional hemisphere of the brain is associated with pathological motor control post-stroke.

In order to answer this question, the current study proposes a protocol that involves a motor task on the paretic arm of the stroke participants when they are receiving tactile stimulation to fingers, as compared to the scenario that which they are only receiving tactile stimulation without any motor output. Our key hypothesis is that following a unilateral motor stroke, a hemispheric shift in somatosensory processing provides altered sensory feedback to support increased reliance on contralesional cortico–bulbospinal pathways for moving the paretic arm in hemiparetic stroke. The laterality index of somatosensory evoked potentials (SEPs) is computed to test this hypothesis with the assumption that contralesional sensory activity would be increased during the motor task in stroke as more sensory information is needed as the feedback for the movement control.

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II. MATERIALS AND METHODS

A. Data Collection

The EEG data in this study were collected by the Brainvision ActiCap Snap system with ActiCHamp amplifier, utilizing

64 channels at 5000 Hz from seven chronic hemiparetic stroke subjects (IRB # 14309), compared to the data collected from eight healthy controls in our previous study [7]. Participants were seated in a Biodex chair, with their forearms securely restrained parallel to their legs. The shoulder of the paretic arm was positioned at a 45-degree angle, and the elbow was kept near 90 degrees to minimize arm movement. Then, they received electrical tactile stimulation with a 200 µs pulse duration and 500 ms inter-stimuli interval on the index finger of their paretic hand. The stimulation intensity was set at twice the sensation threshold (the minimum stimulus level required for the subject to feel the sensation). If twice the sensation threshold caused pain to the subject, the intensity was reduced to a level right below the pain threshold.

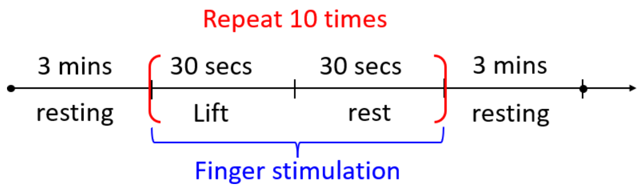

Fig. 1: Illustration of the experimental design.

The subjects underwent separate lift and rest trials lasting 30 seconds during finger stimulation, constituting a single round. During the lift trial, participants were required to attempt to lift their arm smoothly from the shoulder, providing voluntary effort against the forearm restraints at the best level that they could hold for 30 seconds, followed by a 30-second rest. This process was repeated 10 times for each participant, as illustrated in Figure 1.

TABLE I: DEMOGRAPHICS OF STROKE SUBJECTS. “LESION”: LESION SIDE; “AFFECTED”: PARETIC HAND (L: LEFT SIDE; R: RIGHT SIDE); “FM-UE”: FÜGL–MEYER UPPER EXTREMITY SCORES (TOTAL: 66).

Subject	Lesion	Affected	FM-UE	Years after Stroke	Sex
SL004	L	R	44	4	M
SL003	L	R	6	2	M
SL005	R	L	30	1	F
SL010	R	L	35	4	F
SL011	R	L	61	7	M
SL012	R	L	58	1	F
SL013	L	R	24	3	F

B. Data Processing and Quantifying

The collected data underwent rereferencing, a high-pass filter with a cutoff frequency of 0.5 Hz, and Infomax Independent Component Analysis (ICA). Following the ICA reversal, the eyeblink component and repetitive artifact data were mostly discarded manually. The data over 40 ms pre- and 150 ms post-stimulus period will be baseline-corrected and averaged to extract the Somatosensory Evoked Potentials (SEP) [8], using the EEGLAB toolbox [10]. To eliminate artifact spikes caused by finger stimulation pulses, all data between 0.08 and 0.0826 seconds for each epoch were removed. For missing data, cubic spline interpolation was applied using EEG channel data within $\leq$ 50 ms around the stimulation event time from -0.05 to 0.0526 ms. After the artifact removal, the data underwent further filtering using a 60 Hz notch filter and a 1-45 Hz bandpass filter. We compute somatosensory evoked potentials on the channels over the sensorimotor areas in both hemispheres, which are C1/C2, C3/C4, C5/C6, CP1/CP2, CP3/CP4, CP5/CP6 following the 10/20 EEG recording system (see Fig. 2).

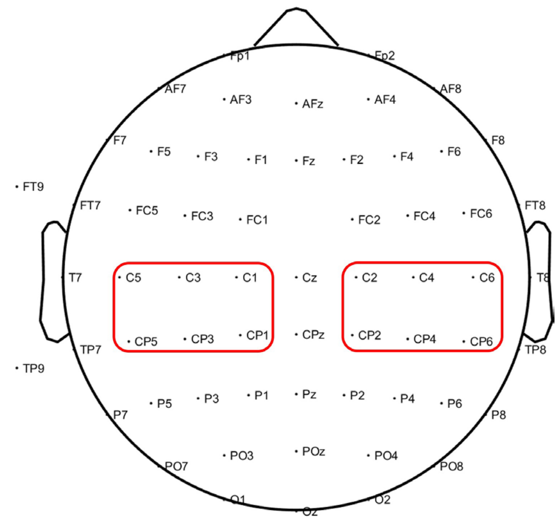

Fig. 2: Six channels covered by the motor cortex are investigated in the study. Average values from these channels are used to calculate LI.

To evaluate the degree of lateralization between the sensorimotor areas of two hemispheres, we applied the laterality index (LI) [5], [11] to quantify lateralized somatosensory evoked potentials (SEPs). The index is defined by the equation:

$$LI = \frac{\text{Contralateral} - \text{Ipsilateral}}{\text{Contralateral} + \text{Ipsilateral}} \tag{1}$$

where it indicates the difference in signal power of SEP components between the contralateral and ipsilateral hemispheres to the affected arm in the sensorimotor areas shown in Figure 2. We calculate the LI value by averaging the signals from the six channels in each hemisphere and focus on the early SEP components that occur at 50 ms (initial sensory processing), i.e., P50, and 100 ms (fast feedback to motor control), i.e. N100, since this is the period when fast somatosensory processing and feedback occurs for upper limb movement [12]. The higher LI reflects that the signal on the contralateral side is stronger than in the ipsilateral hemisphere, implying a normal brain function. In stroke, a reduced LI indicates that the ipsilateral (contralesional) side takes over functions from the contralateral (lesioned hemisphere) side when the stimuli are applied to the paretic limb. In this study, we specifically investigate the LI of stroke-affected paretic arms during stimulation to understand the functional changes in the sensorimotor system of the brain.

C. Statistical Analyses

The statistical analyses were conducted using the "scipy.stats" package in Python. The study included eight healthy controls (four females) in the resting state from a previous paper [7] in our group and seven post-stroke subjects (four females) (Table I), demonstrating age-matching with an insignificant p-value of 0.8260 under the simple t-test. This ensures that the two study groups have similar ages.

TABLE II: DESCRIPTIVE STATISTICS OF LI. (L: LIFT, R: REST, AND C: CONTROL)

Group	Mean	95% CL Lower	95% CL Upper	Std	Min	Max	Median
P50-L	0.25	-0.73	0.79	0.51	-0.87	0.82	0.29
P50-R	0.36	-0.76	0.80	0.56	-0.96	0.81	0.48
P50-C	0.98	0.90	1.00	0.04	0.89	1.00	0.99
N100-L	-0.13	-0.90	0.90	0.64	-0.92	0.95	-0.32
N100-R	0.58	-0.31	0.97	0.47	-0.40	0.97	0.74
N100-C	0.93	0.72	1.00	0.12	0.72	1.00	1.00

In addition, we specifically separate the P50 and N100 components of SEPs in rest and lift states to investigate the variations in LI over time and to examine potential differences during movement. This exploration aims to provide information for a better understanding of patients' function. Consequently, we divide the data of stroke patients into two parts: lifting and rest statuses. Therefore, the subgroups discussed in this study are P50-L (lifting), P50-R (rest), and P50-C (control), and the same applies to N100 (L, R, C). Descriptive statistics for the six subgroups are shown in Table II. To compare the differences between the subgroups, we implement paired t-tests to evaluate the difference between rest and lift states for P50 and N100 individually for stroke subjects. On the other hand, a two-sample t-test was used to assess the difference between the control (healthy) group and the stroke group. The significant level is determined at $\alpha = 0.05$.

III. Results and Discussion

A. Comparing Lift States and Control Group

The descriptive statistics reveal a significant difference between stroke (both lifting and rest) and control groups. The mean LI for P50 is 0.25 in stroke patients during the lifting task, significantly lower than the healthy control group's mean of 0.98 (Table II). Similarly, for N100 during the lift task, the mean LI is -0.13 in stroke patients, showing a significant deviation from the control group's mean of 0.93. The highly significant p-values of 0.0026 for P50 and 0.0009 for N100, as determined by a simple t-test (Fig. 3 and Fig. 4), underscore the notable impairment in the motor pathway functioning on the lesion side of stroke patients. This implies a shift of certain sensory processing activities from the contralateral to the ipsilateral side, leading to bilateral activities or even ipsilateral dominance during the lifting task.

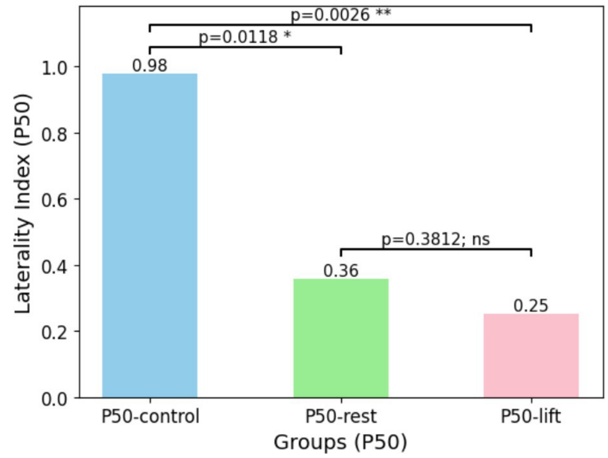

Fig. 3: The comparison of p-values for LI of P50 in the three groups: control vs. rest, and lift status of stroke patients.

B. Comparing Rest States and Control Group

In contrast, during rest states, the analysis indicates a moderately significant difference in P50 compared to the healthy group, with a p-value of 0.0118 (Fig. 3). However, the difference in N100 is marginally below the significance threshold, with a p-value of approximately 0.0817 (> 0.05) (Fig. 4). This suggests that the hemispheric shift of somatosensory processing occurs only at the initial phase of sensory processing around 50 ms when there is no active motor task.

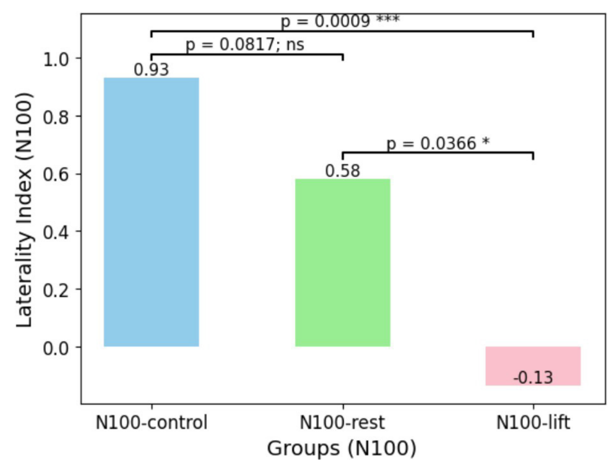

Fig. 4: The comparison of p-values for LI of N100 in the three groups: control vs. rest, and lift status of stroke patients.

C. Comparing Rest and Lift States

A paired t-test is used here to evaluate the significance of the differences between two states (rest and lift) since these data are from the same subjects, differing only in the presence or absence of a motor task.

The results indicate that the LI of N100 shows a more significant difference between lift and rest states (p-value = 0.0366; < 0.05; see Fig. 4), compared to the p-value of P50 for the two states (p-value = 0.3812; > 0.05; see Fig. 3). This suggests a significant shift in function from the contralateral (brain lesion side) to the ipsilateral side during the motor task, as reflected in the latency or time delay measured in milliseconds (ms). Consequently, LI during lift states for P50 (mean LI is 0.25) is larger than that of N100 (mean LI is -0.13) (Fig. 4). This transition from a positive LI in P50 to a negative LI in N100 implies the dynamics of the hemispheric shift in sensory processing. The shift is enhanced at around 100 ms to provide adaptive sensory feedback to the contralesional motor control, as evidenced by a larger contralesional N100 activity.

IV. Conclusion

This study investigates SEPs in two critical components measured in terms of time at around 50 ms and 100 ms: P50 and N100 by laterality index (LI). The goal is to quantify the extent of shifting to the contralesional side from the lesioned side of brain, which is contralateral to the paretic arms, during movement tasks for individuals suffering from hemiparetic stroke.

Overall, the healthy group shows the highest LI, showing normal brain function with the primary signal coming from the contralateral side when they are receiving tactile finger stimulation. In stroke, the hemispheric shift of cortical somatosensory processing occurs resulting in a significantly reduced LI. This hemispheric shift of sensory processing is further enhanced at the N100 trough around 100 ms post-stimulation while stroke participants were performing a movement task. The shift likely provided altered sensory feedback to support the contralesional motor control after a hemiparetic stroke.

In summary, besides quantifying the differences between the healthy control and stroke groups, this study offers insights into the temporal aspect of sensory processing and feedback in injured brains. It indicates a dynamic process in stroke-altered sensory processing and feedback, influencing the shift of sensorimotor functions during motor tasks. This process potentially involves complex interactions between contralateral and ipsilateral sensory-motor pathways. The findings highlight the possibility of time-dependent reorganization of function in the brain during motor tasks, progressing from P50 to N100. This suggests a gradual shift of sensory processing to support the increased reliance on the ipsilateral side and involvement of contralesional cortico-bulbospinal pathways in hemiparetic stroke. We will include more participants in a full study to further test our hypothesis. A multimodal brain imaging approach integrating EEG and MRI will be applied for this purpose as the next step [8].

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