Differential Cortical Responses of Functional and Sensory Electrical Stimulation in Closed-Loop Tremor Suppression for Parkinson's Disease

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***Abstract*— Functional electrical stimulation (FES) and sensory electrical stimulation (SES) are widely used in tremor suppression for Parkinson's disease (PD), however, their therapeutic efficacy varies significantly across individuals. This study investigated the differential cortical effects of FES and SES during closed-loop tremor suppression in PD patient, aiming to identify neurophysiological biomarkers for guiding personalized neuro modulation strategies. We developed an inertial based closed-loop tremor suppression system that delivers out-of-phase FES and continuous SES based on real-time tremor detection. Fifteen PD patients were recruited in tremor suppression trials while surface electroencephalography (EEG) and inertial-based movements of hand and forearm were measured. Both FES and SES significantly reduced tremor amplitude, with FES showing overall greater suppression (hand suppression rate: 60.72% vs. 48.31%, $p > 0.05$; forearm suppression rate: 62.25% vs. 54.41%, $p > 0.05$) where substantial inter-individual variability was observed. EEG analysis revealed that FES induced contralateral beta-band event-related desynchronization (β-ERD), whereas SES elicited beta-band event-related synchronization (β-ERS). These distinct cortical response patterns were significantly correlated with tremor suppression performance (FES β-ERD: $r = -0.629$, $p = 0.012$; SES β-ERS: $r = 0.679$, $p = 0.005$). Resting-state spectral analysis further revealed modality-specific changes in alpha power across sensorimotor regions. These findings revealed functional neurodynamic signatures associated with individual responsiveness to stimulation. The observed β-band oscillatory responses may serve as candidate biomarkers for predicting individual treatment outcomes, offering a potentially biomarker-guided approach for personalized neuromodulation for PD tremor.**

***Index Terms*— Beta oscillations, electroencephalography (EEG), functional electrical stimulation (FES), sensory electrical stimulation (SES), closed-loop tremor suppression, Parkinson's disease (PD).**

I. Introduction

PARKINSON'S disease (PD) is a neurodegenerative disorder predominately characterized by the degeneration of by dopaminergic neuron degeneration in the substantia nigra, leading to hallmark symptoms like resting tremor, rigidity, and bradykinesia [1]. Resting tremor disrupts fine motor control and significantly impacts the quality of life of PD patients [2]. Tremor pathophysiology is associated with dysfunctional oscillatory activity in the basal ganglia-cerebellar-thalamocortical (BG-CTC) circuits [3], which has been a focus of therapeutic interventions.

Neuromuscular electrical stimulation (NMES, particularly Functional Electrical Stimulation (FES) and Sensory Electrical Stimulation (SES), has emerged as a promising approach for PD tremor suppression) [4], [5]. FES typically delivers low-frequency (20–50 Hz), phase-synchronized pulses that induce rhythmic muscle contractions, thereby mechanically counteracting tremor-related movements [6], [7], [8]. In contrast, SES uses higher-frequency stimulation (50–200 Hz) that activates sensory afferents without generating visible muscle contractions [9], potentially modulating central neural circuits via sensory afferent inputs [10]. Both FES and SES can demonstrated efficacy in tremor suppression but significant inter-individual variability in outcomes have been reported [11], [12]. Some patients respond better to FES while others achieve greater benefit from SES. This variability presents

Received 28 March 2025; revised 24 June 2025; accepted 5 July 2025. Date of publication 22 July 2025; date of current version 28 July 2025. This work was supported in part by the National Natural Science Foundation of China under Grant 82372083 and Grant 82471276; in part by the Joint Funds for the Innovation of Science and Technology, Fujian Province, under Grant 2023Y9085; and in part by Tianjin Natural Science Foundation under Grant 23JCYBJC00690. *(Xiaoqi Zhao and Tinglan Huang are co-first authors.) (Corresponding authors: Xiaodong Zhu; Lin Meng.)*

This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Ethics Committee of Tianjin Medical University General Hospital under Application No. IRB2022-YX-182-01, and performed in line with the Declaration of Helsinki.

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Digital Object Identifier 10.1109/TNSRE.2025.3591134

a major clinical challenge: the absence of clear, personalized criteria for selecting the optimal stimulation strategy for each patient. Addressing this gap is essential for advancing individualized tremor management and optimizing treatment outcomes in PD.

Electroencephalography (EEG) has become an effective non-invasive approach for investigating cortical dynamics associated with PD tremors [13]. Cao et al.'s study [14] revealed that Levodopa-induced increases in beta power correlate with tremor reduction. Other studies have also indicated that changes in cortical oscillatory activity [15]—particularly within the beta frequency range (13–30 Hz)—are closely associated with tremor severity [16] and its modulation [17], [18] in PD patients. Moreover, beta-band oscillations [19], [20] are intimately involved in both motor and sensory cortical processing and manifest as event-related desynchronization (ERD) and synchronization (ERS) patterns. Beta ERD is generally interpreted as reflecting cortical activation associated with motor execution [21] and proprioceptive feedback [22], whereas beta ERS is thought to represent cortical inhibition [23], [24] and sensory gating mechanisms [25], [26]. These distinct oscillatory phenomena highlight the complex role of beta activity in sensorimotor integration. Given the established link between beta oscillations and tremor, as well as their role in motor and sensory inhibition, beta-band activity may serve as a promising biomarker to predict treatment outcomes and guide personalized therapy in PD tremor management.

Closed-loop control systems [27] are commonly employed in tremor management to optimize stimulation efficacy by dynamically adjusting electrical stimulation based on continuous feedback from biological signals, typically electromyography (EMG) [28] or kinematic data [29]. The integration of inertial measurement units (IMUs) for tremor detection with synchronized EEG monitoring enables a comprehensive evaluation of both peripheral motor activity and cortical responses. Despite the considerable potential of EEG-based cortical feedback, its incorporation into closed-loop electrical stimulation systems remains limited. Our study seeks to address this gap by implementing a closed-loop system that precisely controls electrical stimulation for tremor suppression while concurrently monitoring cortical activity, thereby enabling the investigation of potential biomarkers to guide personalized therapeutic strategies.

This study presented an IMU-based closed-loop tremor suppression system that integrates out-of-phase FES and continuous SES strategies. The system was tested in 15 PD patients to evaluate its efficiency and investigate the underlying cortical mechanisms of tremor suppression. Crucially, this work goes beyond efficacy comparisons by analyzing the distinct cortical responses evoked by FES and SES — specifically focusing on event-related desynchronization/synchronization (ERD/ERS) patterns and resting-state spectral dynamics. We aimed to explore whether there was any potential neurophysiological biomarker that is differentially modulated by each stimulated strategy and significantly correlated with tremor suppression. The findings will lay the ground work for personalized neuromodulation strategies tailored to individual cortical response profiles, offering a new direction for precision PD tremor management in PD.

TABLE I
PATIENT'S DEMOGRAPHIC INFORMATION

Subject	Age(y)	Sex(M/F)	MoCA	MMSE	MDS-UPDRS III-3.17	MDS-UPDRS III-3.18
PD01	66	F	22	27	L:2	2
PD02	62	M	23	27	L:3	3
PD03	67	F	28	29	R:1	1
PD04	66	M	23	28	L:3	2
PD05	61	M	26	27	R:2	2
PD06	65	M	28	28	L:2	3
PD07	70	F	23	26	R:1	2
PD08	73	F	28	29	L:1	1
PD09	75	M	25	26	L:2	2
PD10	62	M	24	27	R:2	1
PD11	66	M	28	29	R:2	2
PD12	70	F	27	28	L:1	1
PD13	71	M	24	28	R:2	2
PD14	64	M	24	28	L:2	1
PD15	69	M	23	25	L:3	3
Mean± SD	67.13 ±4.14	-	25.07 ±2.22	27.47 ±1.19	1.93± 0.70	1.80± 0.77

II. MATERIALS AND METHODS

A. Participants

Fifteen patients with idiopathic PD were recruited from the Neurological Department of Tianjin Medical University General Hospital. All participants were diagnosed with resting tremors, predominantly affecting the hands and arms. The inclusion criteria were as follows: (1) diagnosis of Parkinson's disease with Hoehn & Yahr stage 1-2; (2) scores of 1-3 on items 3.17 and 3.18 of the Unified Parkinson's Disease Rating Scale III (MDS-UPDRS); and (3) age between 55 and 75 years.

Exclusion criteria included: (1) presence of stress-related disorders, arrhythmias, or other neurological conditions (e.g., cerebrovascular disease, epilepsy, or central nervous system injuries); (2) metal implants in the head, neck, or arms; (3) severe cognitive impairment as determined by the Mini-Mental State Examination (MMSE) and Montreal Cognitive Assessment (MoCA); and (4) inability to cooperate with experimental procedures. All participants were evaluated in a drug "OFF" state.

The characteristics of patients are summarized in Table I. The study was approved by the Ethics Committee of Tianjin Medical University General Hospital (IRB2022-YX-182-01). All participants were fully informed about the study's purpose and procedures and provided written informed consent prior to participation.

Sample size estimation was conducted using G*Power software for the Wilcoxon signed-rank test (matched pairs). Assuming a medium to large effect size (Cohen's $d = 0.8$) and a significance level of 0.05, a sample size of 15 yields a statistical power of approximately 0.80. This sample size was thus sufficient to detect significant differences in tremor performance before and after stimulation.

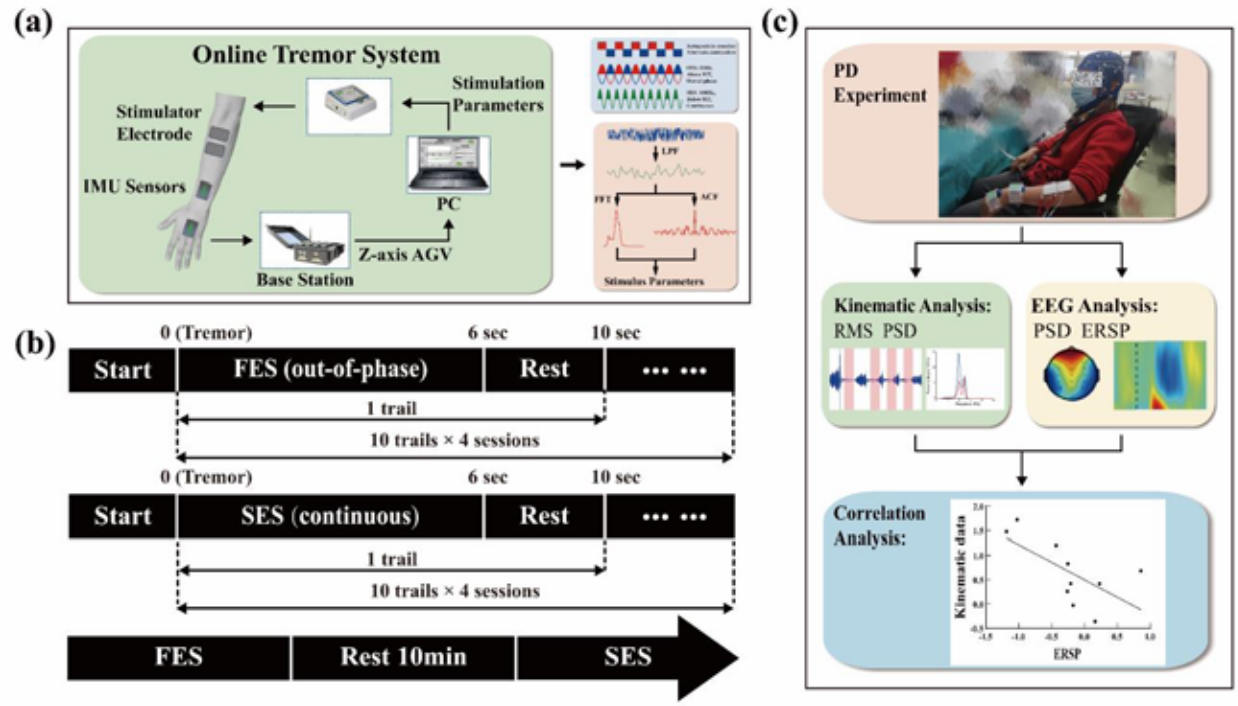

Fig. 1. Study protocol. (a) PD tremor suppression system consists of inertial sensors, a PC for controlling the tremor suppression model and a programmable electrical stimulator, with two different tremor suppression strategies implemented: out-of-phase FES and continuous SES; (b) Experimental procedure. The experiment consists of two stimulation tasks: out-of-phase FES and continuous SES. Upon detecting tremors, electrical stimulation was applied for 6 seconds, followed by a 4-second rest period per trial. Each session consisted of 10 trials. Participants completed 4 sessions of FES, followed by a 10-minute rest period before undergoing 4 sessions of SES. Throughout the experiment, kinematic data from the IMU were continuously recorded and synchronized with EEG data; (c) Data analysis included kinematic analysis, which involved calculating RMS and PSD, as well as EEG analysis, which encompassed ERSP time-frequency features and resting-state spectral power analysis. Finally, the correlation between kinematic features and EEG characteristics was analysised.

B. Closed-Loop Tremor Suppression System

As shown in Fig. 1(a), we developed a closed-loop stimulation system comprising the following hardware: inertial sensors (Delsys, Inc., USA), a PC for controlling the tremor suppression model and a programmable electrical stimulator (RehaStim2, Hasomed GmbH, Germany).

Three inertial measurement units (IMUs) were used to detect tremors: two positioned on the inside and outside of the wrist, and one on the dorsal side of the hand. The sensors were aligned such that the Y-axis pointed toward the ground, and the X-axis of the wrist sensors was parallel to that of the hand sensor. The Acceleration (ACC) and Angular velocity (AGV) were sampled at 74 Hz and processed to identify PD tremors. The PD tremor detection model requires the ACC and AGV data from the IMUs and processed the Z-axis AGV of the hand within a 1-second window. The data were filtered using a fourth-order Butterworth low-pass filter (LPF) with a cut off frequency of 5 Hz. The filtered signal was transformed into the frequency domain using a fast Fourier transform (FFT), and the peak frequency was identified as the dominant frequency. Tremors were detected if the peak frequency exceeded 3 Hz. An autocorrelation function (ACF) was applied to calculate the tremor's half-period, which was used to drive out-of-phase electrical stimulation. Stimulation parameters were updated in real time to match the tremor's oscillations, with recalculation of frequency and half-period estimates every 10 seconds.

The electrical stimulator received stimulation parameters via a serial port and delivered pulses to the extensor carpi radialis (ECR) and flexor carpi radialis (FCR) muscles [4]. Two distinct electrical stimulation strategies were employed, respectively FES and SES. FES was applied in an out-of-phase pattern to alternately stimulate antagonist muscles, minimizing interference with voluntary movement [30]. The timing of alternating stimulation was based on the tremor's half-period. In contrast, SES involved continuous sensory stimulation to provide sustained effects and enhanced tremor inhibition [13]. The stimulation frequency for FES was set at 50 Hz, while SES was applied at 100 Hz, with a pulse width of 300 μs for both modalities. The appropriate stimulation intensity was identified by initially setting the current to 0 mA and incrementally increasing it in 1 mA steps. The motor response was assessed through visual observation and palpation. For FES, the intensity was adjusted to a sufficient level to induce effective wrist flexion or extension without causing discomfort, ensuring it exceeded the motor threshold. For SES, the intensity was set to a level where participants perceived a sensation, but no muscle contraction occurred, ensuring it was above the sensory threshold but below the motor threshold.

C. Experimental Protocol

Participants were seated comfortably in a chair with their arms resting on armrests positioned in front of a desk. For participants with bilateral tremors, the more severely affected

side was selected for stimulation. The skin was prepared using an alcohol swab, and two pairs of square electrode strips (0.1 cm × 0.2 cm) were placed on the muscle bellies of the ECR and FCR. IMUs were attached to the wrist and hand to record motion signals.

As shown in Fig. 1(b), the experiment consisted of two tasks, with each participant undergoing both FES and SES based tremor suppression. Electrical stimulation was triggered upon tremor detection and lasted for 6 seconds, followed by a 4-second rest period per trial. Each session included 10 trials, with participants completing four sessions of FES and four sessions of SES. A 10-minute break was provided between FES and SES sessions.

Motion data were continuously collected via the IMUs throughout the experiment. EEG data were recorded using 32 Ag/AgCl scalp electrodes positioned according to the International 10/20 System, with Cz as the reference electrode. Electrode impedance was maintained below 10 kΩ to ensure signal quality. The EEG signals were sampled at 1024 Hz and band-pass filtered between 0.05 and 100 Hz. Additionally, a 50 Hz notch filter was applied during data acquisition to eliminate power line interference.

D. Data Analysis

Each record from the FES and SES trials was segmented into two datasets: (1) 4 seconds of pre-stimulation data (Stim OFF) and (2) 6 seconds of data during Stimulation (Stim ON). Root mean square (RMS) and power spectrum analyses were applied to the tremor kinematic data to extract time-domain and frequency-domain features, respectively. The mean RMS of the IMUs for each dataset was calculated to estimate tremor suppression amplitude. Power spectral density (PSD) for the Z-axis AGV was computed using the Welch method. Tremor power within the frequency range of 3 to 9 Hz was integrated to evaluate tremor power during Stim ON and OFF conditions. Tremor suppression efficacy was quantified using the suppression ratio (SR), defined as:

$$SR = \left(1 - \frac{P_{ON}}{P_{OFF}}\right) \times 100\% \tag{1}$$

where P_{ON} and P_{OFF} represents the tremor power during Stim ON and Stim OFF, respectively.

The EEG analysis focused on contralateral sensorimotor electrodes (C3 and C4) on the tremor-affected side, which are commonly implicated in tremor and electrical stimulation studies [31], [32], [33], [34]. Event-related spectral perturbation (ERSP) was used to examine spectral power changes related to tremor suppression in the time-frequency domain. ERSP was calculated as:

$$ERSP\,(f,t) = \frac{1}{n}\sum_{k=1}^{n}(F_k\left(f,t\right)^2\right) \tag{2}$$

where n is the number of trials, and $F_k(f,t)$ represents the spectral estimation of the k-th trial at frequency f and time t [35]. Continuous Wavelet Transform (CWT) was employed for time-frequency analysis of EEG, using a scale of 0.5 and a translation of 3. EEG data were divided into 3-second epochs (1 second before and 2 seconds after stimulation). Baseline-normalized ERSP (dB) was calculated for the period from -1 to 2 seconds, relative to a baseline period of 1 second before stimulation. The frequency bands analyzed included delta (1)–4 Hz), theta (4–8 Hz), alpha (8–12 Hz), beta (12–30 Hz), and low gamma (30–40 Hz).

Resting-state EEG data were recorded before and after each stimulation method. The data were segmented into 2-second epochs, and spectral power analysis was performed using the Welch method with a Hanning window. Changes in spectral power before and after each stimulation method were compared.

All data analyses was conducted using MATLAB 2022a (MathWorks, MA, USA) and the EEGLAB toolbox (Swartz Center for Computational Neuroscience; http://sccn.ucsd.edu/eeglab/).

E. Statistical Analysis

The Wilcoxon signed-rank test was used to compare differences of PD tremor performance before and after stimulation, as well as between the two neuromuscular stimulations. EEG data from the two stimulation methods were compared using paired t-tests. To control for multiple comparisons, false discovery rate (FDR) correction [36] was applied using the Benjamini–Hochberg procedure with a threshold of $q < 0.05$. In the ERSP analysis, paired t-tests were conducted across each time–frequency bins while they were applied across all electrode channels for resting-state topographies. Only effects that survived FDR correction were considered statistically significant and are reported in the results. The statistical significance was set at $p<0.05$. Additionally, a correlation analysis between ERSP and tremor suppression was performed using Spearman's rank correlation coefficient. All statistical analyses were performed using SPSS 26 (SPSS Inc., Chicago, IL, USA).

III. Results

A. Tremor Suppression Performance

Fig. 2(a) and (b) illustrates the AGV during tremor suppression with FES and SES, respectively. These results demonstrate the effectiveness of the online tremor suppression system, which triggers electrical stimulation only when tremors are detected. Both FES and SES effectively reduced tremors, while FES showing more pronounced suppression, Table II. Following stimulation, tremors sometimes returned to their previous intensity immediately, while in other cases, they remained suppressed for a period, suggesting that electrical stimulation may have lasting inhibitory effects on tremor activity.

To assess the effects of FES and SES on tremors in different parts of the body, we calculated the RMS of the Z-axis AGV for both the hand and forearm, before and after stimulation. Fig. 2 (c) and (d) show a decreasing trend in RMS values with STIM ON, indicating reduced tremor activity. Wilcoxon signed-rank tests revealed that both FES and SES significantly attenuated tremor amplitude. FES decreased RMS values in the forearm ($Z = -2.726$, $p = 0.006$)

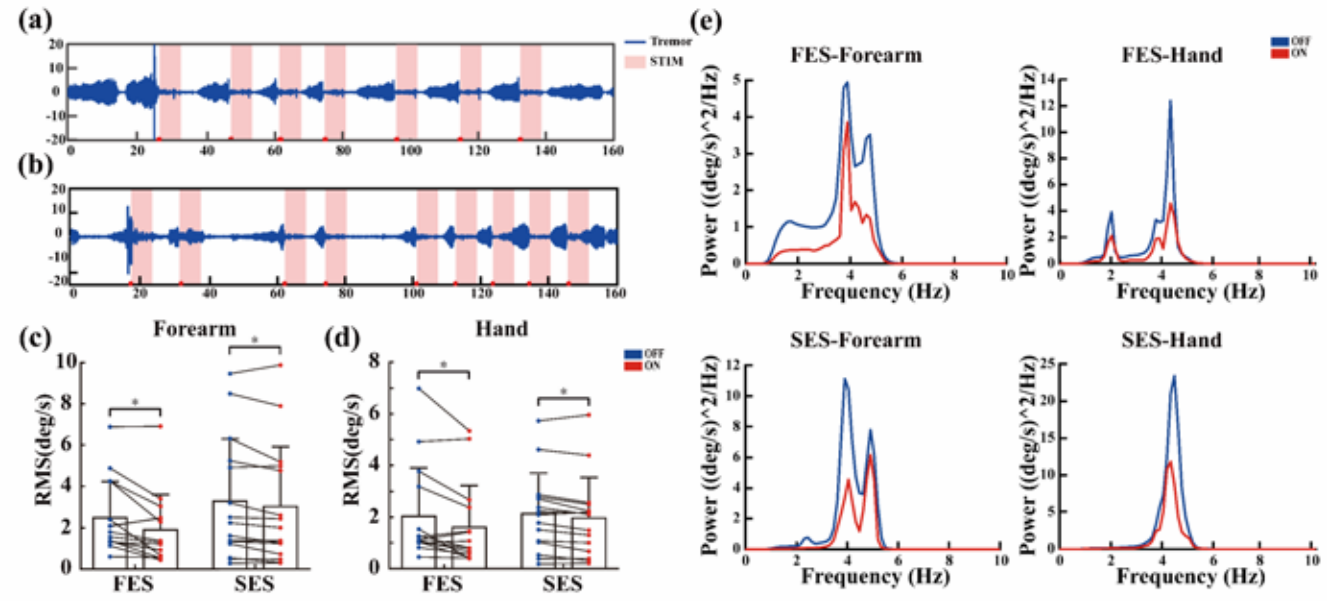

Fig. 2. Tremor suppression perform of a typical patient. (a) Hand AGV during FES trial; (b) Hand AGV signal during SES trial; (c) Comparison of forearm RMS between STIM ON and OFF conditions; (d) Comparison of hand RMS between STIM ON and OFF conditions. * represents $p < 0.05$ (Wilcoxon signed rank test); (e) Power spectral density of forearm and hand AGVs under FES and SES tremor suppression.

TABLE II
SUBJECT STIMULATION INTENSITY AND SUPPRESSION RATIO

Subject	FES(mA)		SR(%)		SES(mA)		SR(%)	
	FCR	ECR	Hand	Forearm	FCR	ECR	Hand	Forearm
PD01	12	15	93.85	81.32	8	10	85.99	87.65
PD02	15	18	26.28	59.37	10	10	40.96	28.09
PD03	15	15	82.87	77.43	10	10	37.99	72.87
PD04	15	15	40.79	22.96	10	10	67.88	61.37
PD05	15	15	29.28	62.91	10	10	30.65	54.56
PD06	18	18	43.81	41.46	10	10	38.53	47.45
PD07	20	20	40.61	52.16	10	10	34.33	18.25
PD08	15	15	80.24	54.12	10	10	36.72	38.40
PD09	20	20	57.33	44.12	10	10	48.48	66.46
PD10	12	12	56.10	64.30	8	8	23.50	42.00
PD11	15	15	90.63	91.55	10	10	76.97	88.44
PD12	15	15	84.55	82.52	10	10	43.80	56.20
PD13	15	15	93.36	96.87	10	10	27.82	26.38
PD14	24	24	49.91	60.06	10	10	81.03	90.60
PD15	15	18	41.26	42.54	10	10	49.94	37.36
Mean ±SD	16.07±3.17	16.67±2.99	60.72±24.33	62.25±20.60	9.73±0.70	9.87±0.52	48.31±20.09	54.41±23.37

and hand ($Z = -2.499$, $p = 0.012$), and SES attenuated tremor in the forearm ($Z = -2.385$, $p = 0.017$) and hand ($Z = -2.442$, $p = 0.015$), with all changes reaching statistical significance. During electrical stimulation, the average tremor power decreased significantly, further indicating tremor suppression, as shown in Fig. 2(e). The SRs for each patient are detailed in Table II. When the system was active, the mean SRs (mean ± standard deviation) in hand were 60.72 ± 24.33% for FES and 48.31 ± 20.09% for SES. In the forearm, the mean SRs were 62.25 ± 20.60% for FES and 54.41 ± 23.37% for SES. Although Wilcoxon signed-rank tests indicated that FES exhibited stronger tremor suppression compared to SES in both the forearm ($Z = -0.966$, $p = 0.334$) and hand ($Z = -1.533$, $p = 0.125$), these differences did not reach statistical significance.

B. ERSP Results

Fig. 3(a) illustrates the mean ERSP for FES and SES during tremor suppression. In the beta band, FES and SES demonstrated contrasting oscillatory patterns: FES induced a pronounced ERD, whereas SES induced an ERS pattern. A paired t-test revealed a significant reduction in beta band oscillations within the frequency range of 26-29 Hz during FES compared to SES, occurring between 120-490 ms. Conversely, SES significantly increased beta band oscillations

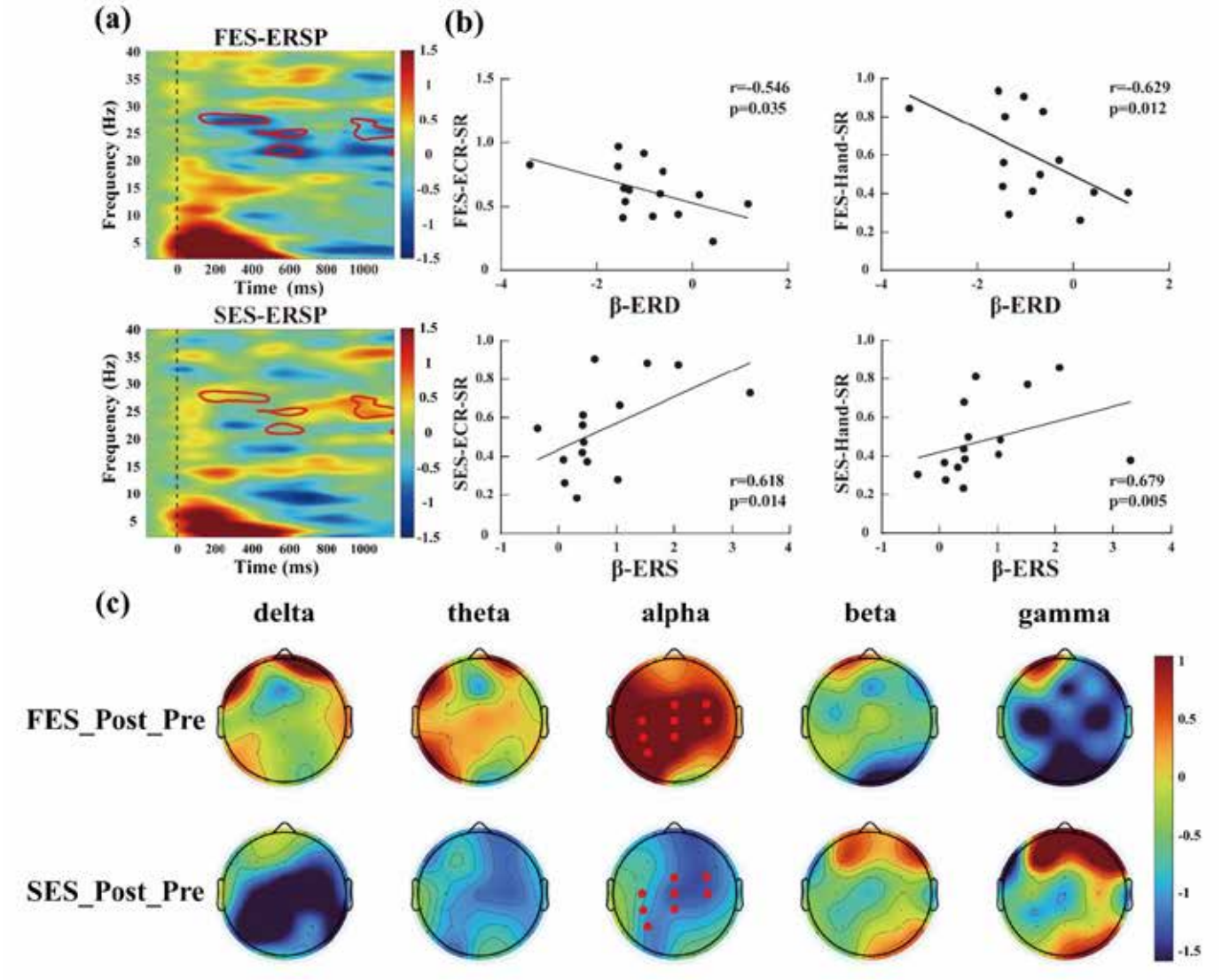

Fig. 3. Results of cortical response induced by FES and SES and their correlation with tremor characteristics. (a) ERSP induced by FES/SES intervention at electrode position C3/C4. The red outline presents significant differences of FES-induced ERD and SES-induced ERS after FDR correction. (b) Correlation analysis between electrical stimulation-induced ERD/ERS values and the tremor characteristics when FES/SES STIM ON. (c) Brain topography of the relative power of EEG rhythms changes between post and pre FES/SES. Channels marked with red dots denote statistically significant differences after FDR correction.

within the ranges of 21–23 Hz (480–680 ms) and 23–28 Hz (930–1170 ms, $p<0.05$).

Correlation analysis further highlighted the relationship between cortical beta band oscillations and tremor suppression. Regions with significant differences in ERSP were identified, and the mean values within specified frequency bands and time intervals were computed. These values were correlated with tremor suppression performance. Beta ERD patterns induced by FES were significantly correlated with SRs in both the forearm ($r = -0.546$, $p = 0.035$) and hand ($r = -0.629$, $p = 0.012$). Meanwhile, beta ERS patterns elicited by SES showed positive correlations with SRs in the forearm ($r = 0.618$, $p = 0.014$) and hand ($r = 0.679$, $p = 0.005$).

C. Resting-State EEG Power Spectrum

As shown in Fig. 3(c), FES induced a significant increase in alpha-band power within sensorimotor regions, including the frontoparietal, central, and part of the parietal cortex, whereas SES caused a significant decrease in power in these regions ($p = 0.0489$). In the beta band, FES led to power reductions in localized areas of the frontal and occipital lobes, while SES induced increases in beta power in these regions. However, the differences observed in the beta band did not reach statistical significance.

IV. Discussion

This study introduced a novel dual-modal framework that integrates IMU-based tremor detection with synchronized EEG monitoring in a closed-loop stimulation system. This design enables real-time evaluation of cortical responses during tremor suppression using both out-of-phase FES and continuous SES. To our knowledge, this is the first study to directly compare the cortical signatures associated with FES and SES

within a closed-loop paradigm and to link these neural patterns to differential suppression outcomes. More importantly, we propose beta oscillatory activity as a functional biomarker to characterize individual treatment responses. This biomarker-driven, dual-modal framework represents a novel and practical approach to guiding personalized neuromodulation strategies, offering a meaningful advancement in precision tremor treatment for PD.

In this study, RMS analysis confirmed that both FES and SES significantly reduced tremor amplitude in PD. Consistent with Dosen et al. [11], FES demonstrated superior suppression efficacy compared to SES, with SRs for FES over 50%, aligning with previous studies on closed loop out-of-phase strategies. However, similar to the results reported by Habibollahi et al. [12], although FES showed higher SRs than SES in both the hand and forearm, these differences did not reach statistical significance ($p > 0.05$). Notably, considerable variability was observed at the individual level. In some participants, FES achieved greater tremor suppression in the hand, whereas SES was more effective in the forearm. The FES's efficacy in hand tremor suppression likely stems from its direct stimulation of targeted muscle groups and precise out-of-phase strategies combined with higher stimulation intensity [4]. This aligns with previous studies, showing FES's superiority in tremor suppression. In contrast, SES was more effective in suppressing forearm tremors, consistent with Hao et al. [37], likely due to the SES's ability to activate the Ia pathway, reduce motor pool excitability, and inhibit tremor signals in muscles not directly stimulated. In others, SES outperformed FES across both regions. Furthermore, analysis of hand AGV signals revealed that FES provided immediate tremor attenuation, while SES showed a gradual effect with sustained reduction post-stimulation. These results underscore a critical clinical challenge: substantial inter-individual variability exists in response to different stimulation strategies. This variability highlights the pressing need for reliable biomarkers capable of guiding personalized treatment selection, enabling the optimization of stimulation paradigms for each individual patient.

We observed distinct cortical response patterns induced by two stimulation strategies: FES elicited contralateral β-ERD while SES induced β-ERS. These differential patterns likely reflect divergent modes of cortical engagement. Prior study has suggested that β-ERD is associated with motor execution and proprioceptive feedback [38], [39], potentially reflecting increased cortical excitability driven by FES-induced muscle contractions. In contrast, SES modulates the central nervous system via high-frequency stimulation below the motor threshold, which activates sensory afferent pathways without producing visible muscle contraction [30]. Both stimulation frequency and intensity are known to significantly modulate cortical excitability [40]. Subthreshold sensory input may potentially be interpreted by the central nervous system as non-movement-related, thus inhibiting cortical excitability [39], [41], [42]. Additionally, high-frequency stimulation has been shown to induce pre- or postsynaptic inhibition, evidenced by a decrease in the H-reflex amplitude [43].

Two principal mechanisms have been proposed for SES-induced tremor suppression [4], [5]: (1) The spinal modulation hypothesis suggests that SES activates afferent fibers to transmit sensory signals to central circuits, interfering with the generation and propagation of tremors. (2) The spinal cord modulation hypothesis posits that SES can reduce the excitability of spinal motor neuron pools or modulate corticospinal transmission, particularly through the regulation of antagonist muscle activity. β-ERS after voluntary movement or sensory stimulation has been typically considered an inhibitory state of cortical activity [23], [24], especially related to sensory gating and functional motor inhibition [25], [26] we interpret the SES-induced β-ERS as a synchronized cortical response to peripheral sensory input, potentially indicative of an inhibitory modulation within the sensorimotor network. However, we do not consider this to be direct evidence of a causal suppression mechanism. Due to the absence of more multimodal data, we cautiously interpret β-ERS as a stimulation-evoked cortical pattern that may correlate with tremor suppression, rather than confirm a mechanistic role.

Evidences from resting-state EEG spectral power analyses further support this distinction. Fig.3(c) showed an increased alpha-band power changes after FES and a decreased alpha power after SES in sensorimotor-related regions including the frontoparietal, central, and parietal regions. Alpha oscillations reflect cortical inhibition after motor activity [44], [45]. Conversely, decreased alpha power after SES indicates enhanced sensory input processing and increased neural network modulation demands for tremor suppression [46], [47], [48]. These results suggest the two modalities modulate cortical networks in distinct ways.

The observed correlations between beta-band activity and stimulation effectiveness indicate that β oscillations may serve as functional biomarkers to assess individual responsiveness to FES and SES. The finding is consistent with previous study that abnormal β-band oscillations in the BG-CTC are closely associated with motor symptoms and tremors in PD [49]. During both the onset and maintenance of tremor, decreased β-band power has been observed in regions such as the subthalamic nucleus (STN) and motor cortex [16], [50], [51], [52]. The beta oscillations have been used in closed-loop neuromodulation systems as real-time feedback signals to dynamically adjust stimulation. In particular, beta-driven adaptive deep brain stimulation (DBS) systems have shown notable improvements in treatment efficacy and reductions in side-effects compared to conventional open-loop approaches [17], [53]. Furthermore, non-invasive neuromodulation approaches, like transcranial magnetic stimulation (TMS) and transcranial direct current stimulation (tDCS), have begun incorporating beta-band activity to tailor intervention protocols for individual patients [54], [55]. Although the precise neural mechanisms underlying tremor suppression by FES and SES remain under investigation, our findings reveal that these modalities evoke distinct cortical beta-band signatures—FES inducing β-ERD and SES eliciting β-ERS. These patterns were significantly associated with individual tremor suppression outcomes, indicating that they are not only markers of stimulation-specific

cortical engagement but also potential predictors of therapeutic responsiveness.

These beta oscillation signatures are stable, accessible through non-invasive EEG, and quantifiable in real time, making them ideal candidates for clinical biomarkers. Their ability to reflect patient-specific responses to different stimulation types positions them as valuable tools for guiding parameter selection and optimizing neuromodulation strategies [18]. In the future, beta oscillations are expected to play an essential role in future clinical systems for precision tremor treatment. By enabling individualized adjustments in stimulation strategy and intensity, beta-guided approaches could significantly enhance the efficacy and personalization of both invasive and non-invasive neuromodulation therapies.

This study has several limitations. Firstly, the observed correlations between beta oscillations and tremor suppression are statistical and do not imply causality. Existing evidence suggests that beta activity likely reflects neural responses to stimulation rather than direct suppression mechanisms. Given the potential role of cortico-muscular synchronization in PD tremor [31], [56], future studies incorporating additional modalities such as EMG and cortico-muscular coherence (CMC) analysis are needed to clarify central-peripheral interaction mechanisms. Secondly, the relatively small sample size and short intervention duration limit the assessment of long-term efficacy. Prior research [57] has shown that sustained stimulation over longer periods can produce meaningful therapeutic benefits. Future studies should include larger cohorts and extended follow-up to evaluate the durability of FES and SES effects and refine stimulation protocols accordingly. Finally, we did not systematically compare different stimulation parameters (e.g., frequency, intensity, duration), which may influence both treatment outcomes and neural responses. Future investigations should explore parameter optimization using EEG-derived biomarkers such as beta oscillations, to support the development of truly personalized neuromodulation strategies for tremor management in Parkinson's disease.

V. Conclusion

This study presents a novel closed-loop tremor suppression framework that integrates IMU-based stimulation control with synchronized EEG monitoring to investigate the cortical effects of FES and SES in PD. While both FES and SES effectively suppressed PD tremors, they elicited distinct cortial beta-band response. Notably, changes in beta oscillations were significantly correlated with tremor suppression, suggesting that beta activity not only reflects functional neural responses to stimulation but also holds promise as a biomarker for individualized therapeutic guidance. These findings provide a promising foundation for biomarker-driven and personalized neuromodulation for PD tremor.

Acknowledgment

The authors thank all patients for their participation in this study. They declare that there is no conflicts of interest.

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