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Negative emotion modulates postural tremor variability in Parkinson's disease: A multimodal EEG and motion sensor study toward behavioral interventions

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ABSTRACT

Background: Despite clinical observations of emotion-tremor interactions in Parkinson's disease (PD), the neurophysiological mechanisms mediating this relationship remain poorly characterized.
Methods: This study employs a multimodal approach integrating 16-channel electroencephalography (EEG) and inertial motion sensors to investigate emotion-modulated postural tremor dynamics in 20 PD patients and 20 healthy controls (HCs) during standardized video-induced emotional states (positive/neutral/negative).
Results: Key findings demonstrate impaired negative emotional processing in PD, manifested as paradoxical increases in subjective valence (pleasure-displeasure ratings) coupled with reduced physiological arousal. Tremor variability predominantly correlated with negative emotional states, showing a negative association with valence scores and positive correlation with arousal levels. EEG analysis identified differential beta-band power modulation in prefrontal (Fp1/Fp2) and temporal (T3/T4) regions during negative emotion processing. These results suggest that emotion-driven tremor fluctuations in PD originate from dysfunctional integration of limbic and motor networks.
Conclusion: These findings establish emotion-modulated tremor as a distinct PD phenotype, informing the development of closed-loop biofeedback systems for personalized neuromodulation.

Introduction

Parkinson's disease (PD) is the second most common neurodegenerative disorder, impacting motor, cognitive, and emotional functioning. Tremor, defined as involuntary, rhythmic body movement, affects approximately 70 % of PD patients and can hinder their ability to perform daily activities, particularly mobility-related tasks (Elias and Shah, 2014; Bhatia et al., 2018). Parkinsonian tremors manifest in three principal forms: rest, action, and postural tremors (Dai et al., 2015). Although not life-threatening, postural tremor—defined as rhythmic oscillation during sustained anti-gravity positioning—imposes significant functional disability. Approximately 68 % of patients report interference with activities of daily living, particularly tasks requiring precise limb control such as utensil use or buttoning (Xu et al., 2023; Gironell et al., 2018). The cerebellum and basal ganglia are involved in initiating, executing, and terminating movement (Luft et al., 2019), and their dysfunction contributes to tremors and movement impairments in PD (Abusrair et al., 2022; Pasquini et al., 2018). Despite dopaminergic therapies alleviating bradykinesia, 40 % of patients exhibit refractory tremor progression (Bălan et al., 2019; Khatin-Zadeh et al., 2023), underscoring the need for novel intervention targets.

Tremors in PD patients often fluctuate independently of disease progression or treatment, influenced by intrinsic factors such as voluntary activities and cognitive, motivational, and emotional states (Bălan et al., 2019). Emotions are embodied experiences, and both embodiment and emotional processing are affected in PD due to basal ganglia dysfunction (Khatin-Zadeh et al., 2023). Emotion plays a critical role in daily life, manifesting through subjective experiences and internal/-external expressions, significantly impacting behavior regulation and mental health (Berlot et al., 2021). The circumplex model of affect

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proposes that emotions arise from the activation of two underlying neurophysiological systems: valence, spanning from negative to positive, and arousal, signifying the intensity of the emotion experienced (Bliss-Moreau et al., 2020). It is important to note that arousal does not refer to excitement, but rather the strength of the emotion being felt (Russell, 1980). Although it is generally held that tremor variability is related to emotions, direct evidence for such a link is currently lacking, and the pathological mechanisms that generate the association remain unclear.

Electroencephalography (EEG) is a crucial non-invasive method for capturing rapid changes in brain processes, providing high temporal resolution for assessing cerebral activity (Waninger et al., 2020). The beta band (15–29 Hz) is characterized by burst-like dynamics rather than sustained rhythmic activity, with high-power emerging transiently in time (Shin et al., 2017). Proposed to be evident during sensorimotor activity, oscillations in the beta band have garnered significant attention in the field of neuroscience. The use of EEG signals in emotion research on participants has shown promising results, as these signals are recorded from the source of emotion generation, providing an opportunity to enhance our understanding of emotion processing in PD patients (Yuvaraj and Murugappan, 2016). Research indicates that beta-band brain oscillations could serve as a useful measure of emotional stimulus processing (Schubring and Schupp, 2021). Studies have demonstrated that the beta-band power of EEG signals, associated with high frequencies, better captures different emotional states compared to low-frequency bands. The beta-band power is closely linked to the brain's cognitive processing and alert state (Zhang et al., 2024).

The association of PD with cognitive and mood disorders has challenged the longstanding belief that PD is solely a motor disorder (Lafo et al., 2015). Mood symptoms in PD patients are well-documented and can include depression, anxiety, and apathy. It remains uncertain whether these symptoms arise from biological factors or result from difficulties in adapting to the disease's functional limitations (Louis et al., 2012). Depending on the emotion, tremors may improve or worsen. Facial emotion recognition has been shown to be negatively associated with tremor severity in individuals with essential tremors (Auzou et al., 2014). In recent years, wearable sensors have gained popularity for researching human body movement due to their compact size, lightweight, and ability to minimize interference from object movement (Wilken et al., 2019). This study uses RMS (root mean square) to indicate the average magnitude of acceleration or angular velocity in each direction during a complete hand posture trial, RMS effectively addresses accurate measurement of hand tremor variability.

While observational studies have noted emotion-tremor associations in PD, the mechanistic link between affective processing and tremor dynamics remains unexplored. This critical knowledge gap hinders the development of biologically-informed therapies targeting tremor variability. Our study tests the novel hypothesis that dysfunctional cortico-limbic-cerebellar integration mediates emotion-tremor interactions. Based on our findings, guiding PD patients in recognizing and adjusting negative emotions could represent a promising new avenue for tremor therapeutic interventions.

Subjects and methods

Study design and participants

Twenty patients diagnosed with PD, who presentin hand postural tremor as the main clinical manifestation (mean age 60.45 ± 5.43 years), and 20 similarly aged healthy controls (HCs) (mean age 59.40 ± 5.93 years) completed research testing and constituted the study population. Patients were consecutively recruited from the Affiliated Hospital of the Institute of Neurology, Anhui University of Traditional Chinese Medicine. All patients were screened by a movement disorder specialist (G.Q.W.) and considered to have PD based on the diagnostic criteria of the Movement Disorder Society consensus statement (Postuma et al., 2015). Patients were tested in their medication-on condition, and those with comorbid neuropsychiatric disorders, visual or hearing abnormalities, or deep brain stimulator or emotional therapy drug use were excluded. Healthy controls were screened for neuropsychiatric disorders and visual or hearing abnormalities and excluded if present. Patient demographic data, neurological history, and clinical classification were collected using a standardized template. The Fahn-Tolosa-Marin Tremor Rating Scale (FTRS) (Yang et al., 2021) was used to assess tremor severity. In this study, the FTRS was specifically utilized to clinically evaluate postural and intentional tremors in the upper limbs. Total FTRS scores range from 0 (no tremor) to 84 (severe disability), with each 1-point increase representing 12.5 % functional decline.

Emotion-inducing video materials and EEG signal acquisition

Emotional elicitation can be achieved using external stimuli and internal responses. The stimulation methods commonly used by researchers aim to induce different emotions in participants through external stimuli, such as pictures, music, and videos (Bălan et al., 2019). In our experiment, we used video clips with high emotional valence as stimulus materials to induce emotions in the participants. The emotion-induced video materials used in this study are obtained from the SJTU Emotion EEG Dataset (https://bcmi.sjtu.edu.cn/~seed) (Zheng and Lu, 2015). The EEG brainwave dataset was designed to classify emotions into positive, negative, and neutral categories. Six Chinese film clips (positive 2, neutral 2, and negative emotions 2) were chosen from the pool of materials as stimuli used in the experiments (Table 1). The selection criteria for the film clips are as follows: (a) the length of the whole experiment should not be too long in case it will cause the subjects to have fatigue; (b) the videos should be understood without explanation; (c) the videos should elicit a single desired target emotion. The duration of each film clip is approximately 4-minute epochs to capture the variations in brainwave patterns corresponding to different emotional states. Each film clip is well edited to create coherent emotion eliciting and maximize emotional meanings.

We recorded 16-channel EEG signals using the Sirius BB EEG (EB Neuro S.P.A, Italy): Fp1-A1、Fp2-A2、F7-A1、F8-A2、F3-A1、F4-A2、C3-A1、C4-A2、T3-A1、T4-A2、T5-A1、T6-A2、P3-A1、P4-A2、O1-A1、O2-A2 based on the international 10–20 system (Fig. 1-A). The EEG signal acquisition showed a sensitivity of 10μV/mm, a temporal resolution of 10 sec/pg, and a low-pass filtering at 30 Hz. The power and amplitude of 16 leads in different frequency bands were obtained by spectral analysis. For each channel, the relative beta-band power was computed by dividing the power in the beta-frequency range by the sum of the power in the four key frequency bands used in the original study (Bučková et al., 2020).

Quantitative measurement of postural tremor

Bluetooth 5.0 motion sensor (Wit Motion Shenzhen Co., Ltd.) module integrates a high-precision gyroscope, accelerometer, and geomagnetic field sensor. Using a high-performance microprocessor advanced

Table 1
The emotion-inducing video material of the film clips in the experiments.

Emotion lable	Video number and name	Video playback time (minute)
Positive video	1. Lost in Thailand	00:03:19
	2. Flirting Scholar	00:04:26
Neutral video	3. World Heritage in China-Huangshan Mountain	00:03:04
	4. World Heritage in China- Suzhou Gardens	00:03:41
Negative video	5. Back to 1942	00:04:00
	6. Tangshan Earthquake	00:04:18

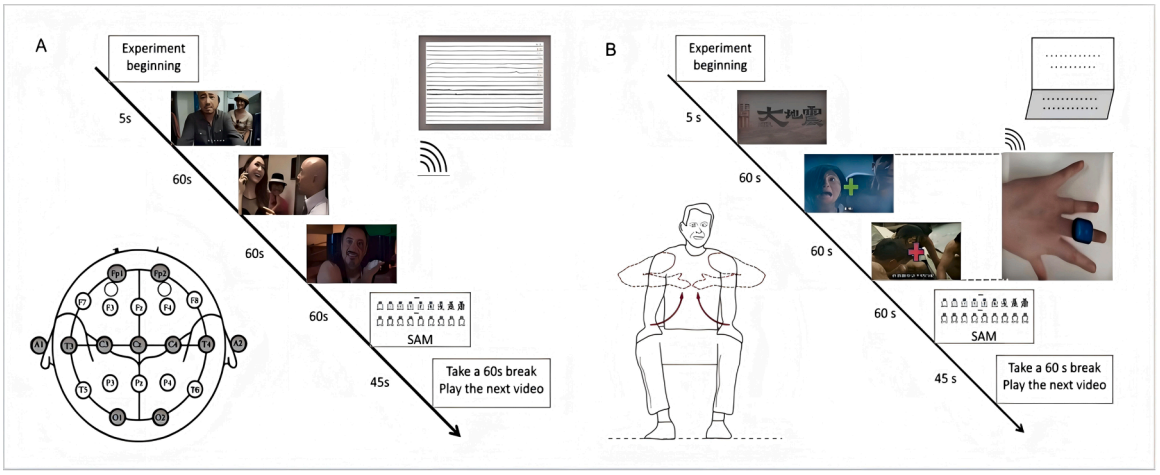

Fig. 1. Example of the experimental process operation. (A) In experimental tasks and procedures under the emotion-inducing video, a schematic diagram of the electrode positions. (B) In experimental tasks and procedures under emotion-inducing video, hand task posture changes during sitting.

dynamic solution and Kalman dynamic filtering algorithm, we can quickly solve the current real-time motion attitude of the module. Model number: WT9011DCL; Weight: 9 g; Dimensions: 23.5*18.7*11.6 mm; Battery capacity: 130 mAh; Operating current: 14 mA; Range: acceleration ± 16 g, angular velocity ± 2000° / S, magnetic field ± 2 gauss, angle X / Z ± 180° Y ± 90°; Resolution: acceleration 0.5 mg/LSB, angular velocity 0.061 (°/ S) / LSB, magnetic field 0.0667 mG / LSB, Angle 0.0055 °/ LSB; Accuracy: X and Y axis 0.2°, Z axis 1°; Transmission distance: using Bluetooth 5.0 technology, Up to 50 m (m); Communication mode: Bluetooth 5.0; Output content: 3 axis acceleration (g), 3 axis angular velocity (°/ s), 3 axis Angle (°); Output frequency: 0.2 Hz~200 Hz; The sampling frequency is set at 51.2 Hz.

Tasks and experimental procedure

This study included two experimental sections: EEG changes in response to emotionally evocative video in procedure A, and tremor variability in response to emotionally evocative video in procedure B. Due to technical constraints in simultaneous signal acquisition, EEG recordings (Procedure A) and tremor measurements (Procedure B) were conducted in separate sessions. To minimize confounding factors, both procedures were performed at the same time of day (3:00 PM) under identical environmental conditions, with a minimum 24-hour interval between sessions. Subjects were introduced to the study's purpose and requirements before testing, which involved self-reporting emotional stability, understanding study content, and ability to cooperate with the testing procedure. Participants were seated comfortably in a leg press, and instructed to keep their heads as still as possible and avoid excessive blinking. One of the most popular self-reporting tools used in our study was the Self-Assessment Manikin (SAM) (Bradley and Lang, 1994). The SAM is a self-reporting scale that measures pleasure, arousal, and dominance using a series of graphic abstract characters horizontally arranged according to a 9-point Likert scale. For valence, ratings ranged from unpleasant (1) to neutral (5) to pleasant (9). For arousal, ratings ranged from calm (1) to neutral (5) to very excited (9). Each emotive state was then mapped into one of three classes based on valence and arousal. The test was suspended if the participant reported emotional instability. Testers included 2 professionally trained permanent personnel. The entire experimental session lasted approximately 40 minutes. Data collection was spread over 2 days to minimize participant fatigue and ensure recording reliability.

Experiment procedure A

Before beginning Experiment A, the EEG cap is placed on the subject's scalp. The sensors are connected sequentially through the application of electrolyte gel after cleaning the sensor gaps with isopropyl alcohol. The circuit impedance was maintained below 5 kΩ for all electrodes before each session. Participants were instructed to sit comfortably in the leg press while keeping their heads as still as possible and avoiding excessive blinking. There were a total of 3 trials for Experiment A. There was a 5 seconds (s) hint before each clip, 45 s for self-assessment, and 60 s to rest after each clip in one session. The clips were played in the order of 1–3–5. For feedback, the participants were instructed to report their emotional reactions to each film clip by completing the self-reporting questionnaire immediately after watching each clip, (Fig. 1A).

Experiment procedure B

Before Experiment B, the motion sensor was affixed to the middle finger of one hand with the Y axis of the sensor pointing toward the fingertip. There were a total of 3 trials for Experiment 2. There was a 5-second hint before each clip, 45 seconds for self-assessment, and 60 seconds to rest after each clip in one session. The clips were played in the order 2–4–6. During the experiment, subjects sat in a chair with their back away from the backrest and both hands on their knees. When the green "+ " symbol appeared in the video, both upper limbs were required to maintain an elbow forward position (bend the elbow and shoulder height, hands fingers straight against each other, and palm down). When the red "+ " prompt appeared after 60 s, participants put their hands down on their knees. Following this, participants were instructed to provide subjective ratings by evaluating their perceived levels of valence and arousal, (Fig. 1A).

Preprocessing of the EEG signals

After the signal acquisition, the selected data were sent for artefact removal or external noise reduction using the EEGLAB toolbox in MATLAB (Delorme and Makeig, 2004). The time-series EEG waveform was pre-processed using the thresholding method to remove movement artefacts; data with amplitudes exceeding 80 μV were discarded. EEG signals were recorded at 150 Hz to capture brainwave pattern variations corresponding to different emotional states. The data were collected in relative amplitude, calculated from 2 to 30 Hz, and then log-transformed (Domingos et al., 2023). Beta-band power modulations were computed using component-based data reduction approaches (Graber and Fujioka, 2020).

Processing of the tremor parameters

Upper computer software (https://wit-motion.yuque.com), driving installation CH340, is primarily used to receive sensor output data and perform storage, management, and display operations. Referring to the Donatas Luksys processing method for tremor signal treatment, triaxial acceleration measurements could reliably quantify resting and postural tremor amplitude in essential tremor (ET) and PD patients (Lukšys et al., 2018; van der Linden et al., 2023). Bluetooth data requires high-pass filtering (a first-order Butterworth filter with 1 Hz cutoff) to remove gravity from acceleration signals, then convert three-axis time-domain data into the frequency domain via Fourier transform. If frequencies on all axes are not equal, the axis with the highest peak power determines the main frequency. Root mean square (RMS) assesses tremor intensity, correlating with actual tremor levels (Jitkritsadakul et al., 2015). The data calculation program was written and run using Matlab R2023b (Mathworks Inc., USA). Based on triaxial acceleration and angular velocity signals from experiments, four tremor parameters were selected to calculate as variability indicators: acceleration frequency (Facc), angular velocity frequency (Fgyr), RMS of acceleration (RMSacc), and RMS of angular velocity (RMSgyr).

Ethics approval and consent to participate

All procedures involving human participants were conducted in accordance with the ethical standards of the institutional and national research committees, as well as the 1964 Declaration of Helsinki and its subsequent amendments. The study was approved by the ethical committee of the Affiliated Hospital of Anhui University of Chinese Traditional Medicine (No: 2023LC-15). Written informed consent was obtained from each participant.

Statistical methods

Statistical analysis was performed using IBM SPSS Statistics, version 26.0 (Armonk, NY, USA). T-tests were utilized for parametric variables. One-way analysis of variance (ANOVA) was employed for multiple comparisons, whereas the Chi-square test was used for frequency analysis. Correlations were assessed using Spearman's rho. A two-sided p-value < 0.05 was considered statistically significant. All reported p-values underwent Bonferroni correction for multiple comparisons across emotional conditions (3 levels) and EEG channels (16 electrodes). Effect sizes were calculated using Cohen's d for t-tests and partial η^2 for ANOVA results. Exact *p*-values are reported unless below 0.001 (denoted as $p < 0.001$).

Results

A total of 20 patients and 20 HCs completed the tests of this study. The demographics and clinical characteristics of participants are summarized in Table 2. There was no significant difference in the mean age at sample collection of the two groups ($p = 0.411$) or sex distribution ($p = 0.712$). The patient's mean age was 60.45 years (±5.43), with a mean disease duration of 6.85 years (± 4.20), with a mean FTRS of 27.30 (± 6.03).

Comparison of emotional valence and arousal during emotional video stimuli in PD and HC groups

In comparison to HCs, PD group patients had consistent assessments of emotional valence and arousal degree during positive and neutral video stimulation ($p > 0.05$), and showed differences in emotional valence and arousal during negative video stimulation ($p < 0.01$), showing an increase in negative emotional valence and a decrease in negative emotional arousal, (Table 2).

Table 2
Demographic Characteristics and Emotional Dimension Scores (Mean ± SD).

	PD n = 20	HCs n = 20	*P*
Male	12 (60 %)	13 (65 %)	0.712
Age (y)	60.45 ± 5.43	59.40 ± 5.93	0.411
Duration (y)	6.85 ± 4.20		
FTRS	27.30 ± 6.03		
Neutral video			
valence	4.00 ± 0.23	3.95 ± 0.28	0.537
arousal	3.98 ± 0.20	3.92 ± 0.39	0.599
Positive video			
valence	7.00 ± 0.80	7.28 ± 0.66	0.241
arousal	7.43 ± 0.86	7.47 ± 0.68	0.953
Negative video			
valence	3.33 ± 0.25	2.68 ± 0.52	0.000***
arousal	6.45 ± 0.48	7.78 ± 0.57	0.000***

Data are the Mean (±SD) or the number (%). Abbreviations: HCs: Healthy Controls; Mean (± SD): Mean ± standard deviation; FTRS: Fahn-Tolosa-Marin Tremor Rating Scale; FTRS-A: vibration amplitude evaluation; FTRS-B: Score the tremor of upper limbs, draw and pour liquid in writing tasks; FTRS-C: tremor dysfunction score, which is used in daily life activities. *** Represents the significance after Bonferroni correction.

Association of clinical indicators with the emotion-tremor index

Spearman Correlation analysis showed that age was positively correlated with FTRS changes in tremor severity ($p = 0.040$), but no direct association with each dimensions of emotion ($p > 0.05$). There was no direct association between disease duration and emotion dimensions and tremor severity ($p > 0.05$), (Table 3).

Comparison of beta-band power values under different emotional video stimuli

Compared with HCs, under three different emotional video stimulation tasks, the beta-band power values in PD group was statistically different in Fp 1, Fp 2 (neutral video); T4, O2 (positive video); and Fp1, Fp2, F3, F4, F7, T3, T4, and T5 (negative video), ($P < 0.05$ or $P < 0.01$), (Fig. 2), (Table 4).

Comparison of tremor variability parameters under different emotional video stimuli

In three different emotional video stimulation tasks, there was no significant difference between Facc and Fgyr parameters ($p > 0.05$). RMS_{acc} and RMS_{gyr} parameters in the negative emotional video stimulation compared with positive and neutral emotional video difference is significant ($p < 0.01$), and no difference between positive and neutral emotional videos ($p > 0.05$), (Table 5).

Correlation analysis of different emotional valence/arousal and tremor variability parameters

Emotional dimensions were associated with postural tremor variability, not tremor severity ($p > 0.05$). Postural tremor variability was positively associated with the valence of neutral emotions ($p < 0.05$), positive correlation with the arousal of negative emotions ($p < 0.05$), and negatively with the valence of negative emotions ($p < 0.01$), (Table 6). This suggests that tremor variability is most pronounced for negative emotions with high arousal and low valence, as well as neutral emotions with high valence.

Discussion

This pioneering multimodal investigation establishes, for the first time, a neurophysiological link between emotional processing deficits

Table 3
Association of clinical indicators with the emotion-tremor index.

Clinical Parameter		FTRS	Neutral video		Positive video		Negative video	
			valence	arousal	valence	arousal	valence	arousal
Age (y)	*r*	.463*	−.200	−.179	.167	.209	.044	−.057
	p	.040	.216	.268	.304	.195	.788	.727
Duration (y)	*r*	.406	.191	−.196	−.095	−.069	−.411	.333
	p	.076	.419	.408	.691	.773	.072	.151

Abbreviations: FTRS: Fahn-Tolosa-Marin Tremor Rating Scale; * $P < 0.05$;

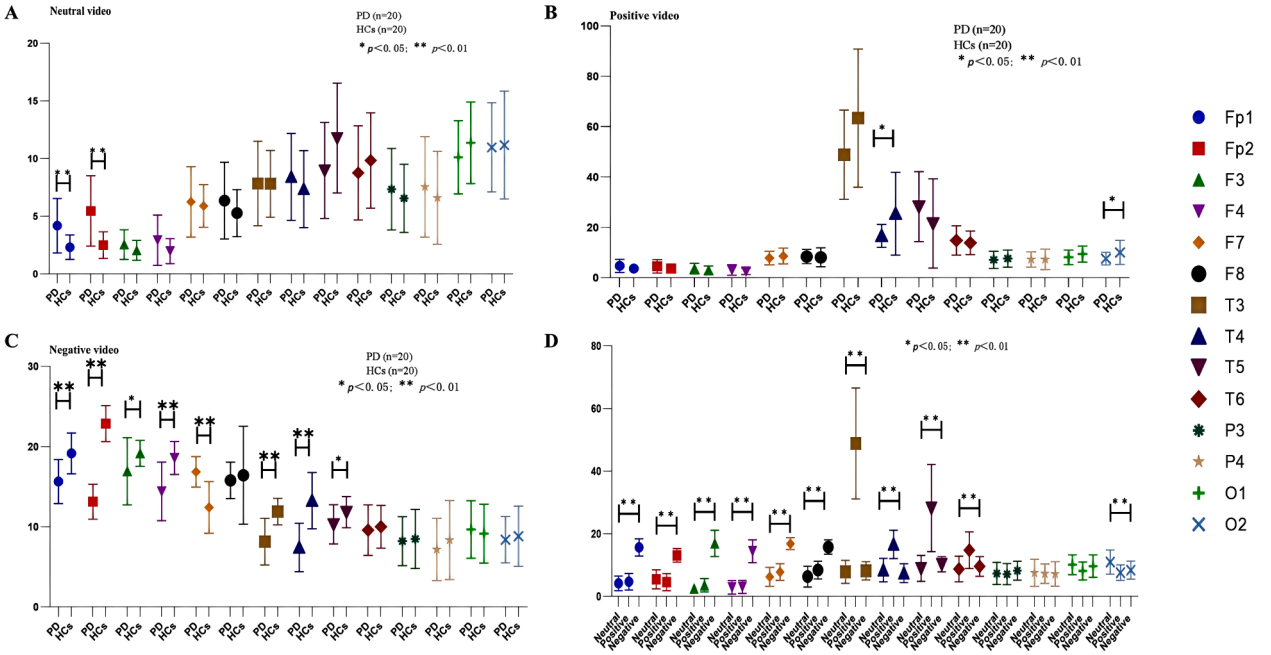

Fig. 2. Comparison of cortical beta-band power values between PD and HCs under different emotional video stimuli. (A) Comparison of beta-band power values under neutral video stimuli. (B) Comparison of beta-band power values under positive video stimuli. (C) Comparison of beta-band power values under negative video stimuli. (D) Comparison of beta-band power values under three different emotional video stimuli in PD groups.

Table 4
Comparison of EEG signal activity under different emotional dimensions in PD and HCs.

	Neutral video			Positive video			Negative video		
	HCs	PD	*P*	HCs	PD	*P*	HCs	PD	*P*
Fp1	2.31 ± 1.08	4.18 ± 2.36**	0.003	3.66 ± 1.74	4.69 ± 2.65	0.155	19.15 ± 2.54	15.64 ± 2.75**	0.000
Fp2	2.49 ± 1.16	5.46 ± 3.05**	0.000	3.67 ± 1.71	4.55 ± 2.71	0.228	22.87 ± 2.25	13.13 ± 2.18**	0.000
F3	2.04 ± 0.86	2.54 ± 1.28	0.155	2.96 ± 1.67	3.58 ± 2.12	0.310	19.16 ± 1.62	16.93 ± 4.19*	0.033
F4	1.97 ± 1.03	2.92 ± 2.18	0.087	2.47 ± 1.26	3.04 ± 2.09	0.305	18.58 ± 2.06	14.42 ± 3.65**	0.000
F7	5.89 ± 1.85	6.24 ± 3.05	0.663	8.61 ± 3.16	7.79 ± 2.68	0.380	12.41 ± 3.23	16.85 ± 1.90**	0.000
F8	5.27 ± 2.04	6.35 ± 3.33	0.222	8.09 ± 3.76	8.41 ± 2.85	0.763	16.43 ± 6.10	15.49 ± 2.28	0.522
T3	7.81 ± 2.89	7.83 ± 3.66	0.991	63.40 ± 27.46	48.87 ± 17.72	0.054	11.90 ± 1.66	8.15 ± 2.92**	0.000
T4	7.35 ± 3.34	8.40 ± 3.77	0.358	25.44 ± 16.46	16.61 ± 4.52*	0.013	13.26 ± 3.51	7.42 ± 3.02**	0.000
T5	11.78 ± 4.76	8.97 ± 4.16	0.054	21.56 ± 17.72	28.25 ± 13.90	0.108	11.83 ± 1.94	10.31 ± 2.45*	0.036
T6	9.83 ± 4.13	8.76 ± 4.08	0.414	13.84 ± 4.70	14.78 ± 5.85	0.582	10.00 ± 2.67	9.58 ± 3.15	0.652
P3	6.55 ± 2.95	7.34 ± 3.53	0.447	7.61 ± 3.40	7.11 ± 3.38	0.642	8.48 ± 3.69	8.21 ± 3.05	0.802
P4	6.59 ± 4.03	7.54 ± 4.35	0.477	7.27 ± 4.09	7.26 ± 3.06	0.992	8.35 ± 4.92	7.18 ± 3.89	0.408
O1	11.36 ± 3.54	10.11 ± 3.17	0.248	9.38 ± 3.18	8.11 ± 2.88	0.193	9.15 ± 3.67	9.66 ± 3.59	0.657
O2	11.17 ± 4.67	10.97 ± 3.86	0.885	10.05 ± 4.78	7.59 ± 2.48*	0.049	8.83 ± 3.75	8.39 ± 2.89	0.679

Compared with the HCs: * $P < 0.05$; ** $P < 0.01$;

and postural tremor dynamics in PD. Through EEG and inertial motion analysis during controlled emotional provocation, we demonstrate that PD patients exhibit dimension-specific emotional dysregulation - manifested as paradoxical increases in negative valence perception coupled with attenuated physiological arousal. Crucially, tremor variability showed a strong negative correlation with negative valence and a positive correlation with arousal level. These findings support the feasibility of employing negative emotion regulation techniques to reduce patient tremor variability and offer novel insights for targeting intractable tremor interventions in future clinical practice.

Postural tremor in PD exhibits high phenotypic heterogeneity in appearance and origin. Studies report that approximately 20 % of PD patients with tremor exhibit postural tremor, including both re-emergent (81 %) and pure postural tremor (19 %) (Dirkx et al., 2018).

Table 5
Tremor parameters under different emotion recognition tasks in PD patients.

	Tremor variability parameters			
	F_{acc} (Hz)	F_{gyr} (Hz)	RMS_{acc} (m/sec^2)	RMS_{gyr} (m/sec^2)
Neutral video	0.52 ± 0.01	5.82 ± 5.51	0.23 ± 0.02	13.52 ± 6.70
Positive video	0.58 ± 0.32	5.77 ± 5.69	0.24 ± 0.03	17.98 ± 10.77
Negative video	0.69 ± 0.54	5.56 ± 5.53	0.28 ± 0.07**##	31.66 ± 15.09**##
F	1.287	0.015	10.498	16.541
p	0.283	0.985	0.000	0.000

Data are the mean/standard deviation. Abbreviations: F_{acc}: acceleration frequency; F_{gyr}: Angular velocity frequency; RMS_{acc}: Root mean square of acceleration; RMS_{gyr}: Root mean square of angular velocity.
Compare with neutral video: * $P < 0.05$; ** $P < 0.01$; Compare with positive video: # $P < 0.05$; ## $P < 0.01$,

Treating postural tremor in PD remains challenging. Levodopa is an effective primary therapy for most patients, controlling troublesome tremors. Compared to bradykinesia and rigidity, the tremor response to levodopa can be inconsistent (Nonnekes et al., 2016). Different neural networks support resting and postural tremor in PD. Postural tremor is more often linked to the cerebello-thalamocortical pathway than resting tremors (Helmich et al., 2021). Postural tremor was associated with reduced serotonin transporter levels, but not resting tremor (Loane et al., 2013). Several physical therapy techniques have shown promise in reducing drug-refractory hand tremors. These include targeted ultrasound, electrical stimulation, wearable orthoses, transcranial low voltage pulsed electromagnetic fields, and virtual reality (Abbasi et al., 2018). However, current evidence supporting their effectiveness is limited by small sample sizes; thus, larger randomized controlled trials with larger sample sizes are needed (Shahien et al., 2023).

Although the exact mechanism of tremor in PD is not fully understood, this symptom differs from bradykinesia and rigidity in that tremor intensity is not correlated with the overall degree of nigrostriatal dopaminergic denervation (Benamer et al., 2000). Both clinical and experimental findings suggest that viewing tremor in PD as a straightforward symptom of dopaminergic denervation of the basal ganglia is inadequate (Dirkx and Bologna, 2022). This suggests the involvement of other brain areas and neurotransmitter systems. The neural circuits controlling tremor and emotional behaviors are intricately and reciprocally linked. The cortico-striato-thalamocortical circuits and the mesolimbic dopamine system, which regulate emotional processing, are believed to play a role in governing neural activity (Péron et al., 2012). Histopathologically, PD is characterized by the gradual, chronic, and selective degeneration of nigrostriatal and mesocorticolimbic dopamine systems (Lagravinese et al., 2018). This makes PD a useful model for assessing the functional importance of these systems. As a result, individuals with PD have difficulty expressing emotions, describing physical sensations, regulating physiological arousal, and interpreting moods (Avanzino et al., 2018). They also have trouble understanding the emotions of others based on prosody and facial expressions (Blakemore et al., 2018).

Emotion arousal plays a crucial role in initiating physiological reactions and preparing the motor system for movement. Compared to pleasant stimuli of the same valence, painful stimuli elicit a more rapid and forceful motor response during upper limb motor tasks (Coombes et al., 2006, 2007). Previous research has suggested that individuals with PD exhibit altered emotional processing, supported by reduced physiological response to emotions, impaired recognition of emotional words, and altered arousal judgments despite normal valence (Drago et al., 2008; Kawamura and Kobayakawa, 2009). As shown in our study, different activation of brain regions in EEG appeared under different dimensions of emotional stimulation.

Our study found that negative affect had increased valence, and decreased arousal in PD patients compared with healthy controls. The increased valence of negative emotions suggests that PD patients have more negative emotional experiences. Compared to healthy individuals, PD sufferers would experience more intense negative feelings or unpleasant reactions when watching a film of negative emotions. The emotional state of individuals at that moment is also reflected in how they interpret emotional cues. Individuals in a depressed emotional state are more likely to interpret events negatively compared to those in a happy emotional state (Lagattuta et al., 2016). The reduced negative emotional arousal suggests that patients exhibit a slower response to negative emotions, a common manifestation in depression, anxiety, lack of motivation, and exhaustion. Apathy and poor mood are primarily caused by abnormal neurotransmitter release in the brain in PD. This can affect individual mood swings and may be accompanied by anxiety and sadness. One common PD symptom is hypomimia, which is characterized by reduced facial expressiveness. This can affect both the expression of emotions and other involuntary facial movements such as blinking. Studies have indicated that individuals with PD have difficulty discerning emotions from facial expressions (Ricciardi et al., 2020). From a pathophysiological perspective, hypomimia has been associated with specific emotion processing abnormalities, including emotional valence and arousal processing, and central dopaminergic deficiency, according to recent clinical and neuroimaging studies in PD (Siquier and Andrés, 2022). These studies have found that high-beta oscillations were linked to activations in subcortical reward networks, including the hippocampus, anterior lateral temporal cortex, posterior cingulate

Table 6
Correlation of different emotional valence/arousal and tremor parameters in PD.

			Tremor severity	Tremor variability			
			FTRS	F_{acc} (Hz)	F_{gyr} (Hz)	RMS_{acc} (m/sec^2)	RMS_{gyr} (m/sec^2)
Neutral video	valence	*r*	.095	−.311	−.235	.125	.171
		p	.690	.051	.144	.444	.291
	arousal	*r*	−.304	.036	−.072	−.109	−.032
		p	.193	.823	.660	.503	.846
Positive video	valence	*r*	−.044	.004	−.030	−.123	−.058
		p	.854	.985	.900	.605	.807
	arousal	*r*	−.061	.026	.031	−.167	−.114
		p	.798	.915	.898	.482	.633
Negative video	valence	*r*	−.230	−.385	−.038	−.519*	−.715**
		p	.329	.094	.874	.019	.000
	arousal	*r*	.240	.360	−.129	.534*	.849**
		p	.308	.119	.588	.015	.000

Abbreviations: FTRS: Fahn-Tolosa-Marin Tremor Rating Scale; F_{acc}: acceleration frequency; F_{gyr}: Angular velocity frequency; RMS_{acc}: Root mean square of acceleration; RMS_{gyr}: Root mean square of angular velocity.
* $P < 0.05$; ** $P < 0.01$

cortex, and ventral striatum, in response to positive feedback (Andreou et al., 2017).

In PD, the relationship between emotion and motor regulation has been gaining attention. Research reveals that emotion perception is intricately linked to action systems, and that motor excitability variations are primarily influenced by arousal levels (van Loon et al., 2010). Additionally, distinct stimuli may activate motor resonance processes rather than emotion-related motor modulations. The effect of emotional valence on motor performance can be either beneficial or detrimental, depending on the stimulus nature (Hälbig et al., 2011; Braine and Georges, 2023). Abnormal processing of emotional valence in subcortical limbic regions is associated with PD. Neural circuits are believed to be critical for integrating sensory, cognitive, and affective data to ultimately guide motor behavior. The motor system is closely linked to neural circuits involved in emotion processing. These circuits regulate emotional behavior, which is vital for survival, and continuously influence ongoing movements (Arioli et al., 2022). Studies suggest emotional processing deficits may be associated with PD. Although the exact processes behind emotion-triggered tremor variability remain unknown, they may arise from movement-related functional changes in the basal ganglia and cerebellum-thalamo-cortical circuit, which desynchronize motor unit firing with voluntary activation (Bliss-Moreau et al., 2020). A recent PET imaging study found that parkinsonian tremor is associated with reduced cholinergic nerve terminal function in the putamen and cerebellar vermis, suggesting a link between these neurological symptoms and underlying neurochemical imbalances (Bohnen et al., 2021). The neuropathology of PD can impact limbic cortical-striatal-thalamocortical circuits in various ways, which may explain the cognitive, motor, and psychiatric symptoms associated with PD (Carey et al., 2021). The manifestation of various movement disorders is thought to be emotionally influenced by the same processes. Emotion and tremor intersect in these circuits and likely form part of a broader pathway, where different components play distinct roles in emotion and tremor expression.

There are two methodological limitations in this study: first, although 4-minute video stimulation can effectively induce acute emotional response (Kreibig, 2010), it cannot simulate the chronic emotional state experienced by PD patients, and may underestimate the cumulative effect of emotional exposure. Future studies can use ecological momentary assessment (EMA) combined with wearable devices to continuously monitor the emotion-tremor dynamic relationship in real scenarios.Second, there is a 24-hour interval between EEG and motion sensor data acquisition, without resolving the millisecond dynamics of cortical-motor coupling despite controlling for confounders through environmental standardization. The latest synchronous EEG-inertial measurement technique has achieved the phase amplitude coupling analysis of β oscillations and tremor dynamics (Craik et al., 2023), and subsequent studies are recommended to adopt this scheme.

Despite clinical observations of emotion-tremor interactions in PD, the neurophysiological mechanisms underlying this relationship remain uncharacterized. Our findings reveal that Parkinsonian tremor variability is predominantly modulated by negative emotional states, showing strong positive correlation with arousal and inverse association with valence. This emotion-tremor coupling, likely mediated by limbic-cerebellar circuits, highlights the therapeutic potential of targeting emotional dysregulation. Biofeedback-assisted strategies (e.g., real-time arousal monitoring with tremor kinematics) may enable dynamic symptom control. Many emotion-regulation techniques, including reappraisal, deep breathing, and meditation, are used as a set of cognitive and behavioral strategies to cope with stress and regulate emotions (McRae and Gross, 2020; Gross, 2002). Clinically, integrating emotion-focused interventions (cognitive reappraisal, mindfulness) with dopaminergic therapies could address both motor and non-motor PD manifestations synergistically. These strategies can effectively manage and regulate negative emotions in PD patients improving tremor symptoms and quality of life.

Conclusions

This study redefines PD postural tremor as a limbic-motor interface disorder, establishing emotion-specific modulation patterns and prefrontal beta oscillations as novel therapeutic targets. Our closed-loop intervention paradigm bridges neurology and psychiatry, paving the way for biologically-informed personalized therapies.

Ethics statement

All procedures performed in the studies involving humans were by the ethical standards of the institutional and national research committee and with the 1964 Declaration of Helsinki and its later amendments. The study was approved by the ethical committee of the Affiliated Hospital of Anhui University of Chinese Traditional Medicine (No: 2023LC-15). Each participant provided written informed consent.

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CRediT authorship contribution statement

Wen Xiao: Writing – original draft, Methodology, Investigation, Data curation. **gongqiang WANG:** Supervision, Project administration, Conceptualization. **Bai Xue:** Formal analysis, Data curation. **Jin Ping:** Validation, Supervision, Methodology, Investigation. **Zhang Pei-zhu:** Validation, Resources, Data curation. **Tong Guang-an:** Formal analysis, Data curation. **Ma Xin-feng:** Visualization, Validation, Software. **Han Yong-zhu:** Project administration, Conceptualization. **Li Pei:** Formal analysis, Data curation. **Lin Kang:** Writing – review & editing, Software, Resources, Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Consent for publication

Not applicable.

Author Contributions

Lin K, Jin P, Ma XF, Tong GA played a role in the plan implementation and wrote and edited the manuscript. Li P, Wen X, Bai X, and Zhang PZ contributed to the investigation process, specifically handling the experiments and data collection. Wang GQ and HanYZ contributed to the formulation or evolution of overarching research goals and aims. All authors contributed to the article and approved the submitted version.

Data Availability

The original contributions presented in the study are included in the

article and supplementary material, further inquiries can be directed to the corresponding author.

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