# Identification of EEG Dynamics During Freezing of Gait and Voluntary Stopping in Patients With Parkinson's Disease

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*Abstract*—**Mobility is severely impacted in patients with Parkinson's disease (PD), who often experience involuntary stopping from the freezing of gait (FOG). Understanding the neurophysiological difference between "voluntary stopping" and "involuntary stopping" caused by FOG is vital for the detection of and potential intervention for FOG in the daily lives of patients. This study characterised the electroencephalographic (EEG) signature associated with FOG in contrast to voluntary stopping. The protocol consisted of a timed up-and-go (TUG) task and an additional TUG task with a voluntary stopping component, where participants reacted to verbal "stop" and "walk" instructions by voluntarily stopping or walking. Event-related spectral perturbation (ERSP) analysis was performed to study the dynamics of the EEG spectra induced by different walking phases, including normal walking, voluntary stopping and episodes of involuntary stopping (FOG), as well as the transition windows between normal walking and voluntary stopping or FOG. These results demonstrate for the first time that the EEG signal during the transition from walking to voluntary stopping is distinguishable from that during the transition to involuntary stopping caused by FOG. The EEG signature of voluntary stopping exhibits a significantly decreased power spectrum compared with that of FOG episodes, with distinctly different patterns in the delta and low-beta power in the central area. These findings suggest the possibility of a practical EEG-based tool that can accurately predict FOG episodes, excluding the potential confounding of voluntary stopping.**

*Index Terms*—**EEG dynamics, freezing of gait, Parkinson's disease, voluntary stopping.**

## I. INTRODUCTION

FREEZING of gait (FOG) is a devastating symptom of Parkinson's disease (PD) in which patients suddenly feel as though their feet have become "stuck to the ground" [1]. Approximately 80% of patients with severe PD are affected by FOG episodes, which often precipitate falls, leading to a high morbidity and the urgent need for nursing home placement [2].

Currently, the pathophysiology underlying the freezing phenomenon is not well understood [3]. Researchers have employed several approaches, such as electromyography (EMG) [4], [5], functional MRI (fMRI) [6]–[11] and electroencephalography (EEG) [12]–[16], to understand the features of FOG in PD patients. The pathophysiology of FOG episodes and the distinct patterns associated with freezing were identified using fMRI-based studies [10], [11]. Although fMRI offers great spatial resolution up to a few millimetres, it is limited by a low temporal resolution due to a slow hemodynamic response, with a delay of up to a few seconds to the onset of neuronal activity [17], [18]. However, EEG signals provide millisecond temporal resolution that enables the capture of rapidly changing brain dynamics during freezing episodes. Therefore, several electroencephalography (EEG)-based studies have also attempted to establish the neurophysiological correlate of FOG in PD. Increased beta power was observed in the subthalamic nucleus during FOG episodes based on the analysis of signals collected from cortical electrodes [14].

The brain dynamics associated with FOG episodes during turning measured using ambulatory EEG revealed significant changes in the high-beta and theta power spectral densities across the occipital and parietal areas during FOG episodes with turning [19]. In addition, EEG dynamics have demon-

strated great potential in identifying the onset of freezing in patients with PD [20]. Indeed, EEG features have been suggested to be useful in predicting the transition from normal walking to freezing by using a 5-s time window before the episode [19], [21].

The advances in EEG have made it an efficient tool for understanding not only FOG episodes but also other ordinary motor tasks related to movements, including walking. For example, two studies [22], [23] have suggested specific roles for EEG activity within particular frequency bands in the completion of ongoing motor tasks. Specifically, this EEG activity includes beta activity during motor preparation, gamma activity during motor commission and gating [24], [25], and theta activity during the processing of conflict-related signals [26], [27]. Additionally, event-related EEG potentials, particularly the EEG signals occurring before the initiation of an action, were found to be useful in identifying the intention to move [28], [29].

Since gait dynamics alone cannot accurately predict freezing episodes or independently distinguish freezing from voluntary stopping, we hypothesise that EEG could be essential for the reliable detection of FOG. Anticipating that the brain dynamics during the transition to freezing can be confidently discerned from those during the transition to voluntary stopping, "real-time" EEG may offer a novel therapeutic intervention for the prediction and alleviation of freezing episodes. Recently, researchers have demonstrated that pathological subthalamic nucleus activity associated with bouts of freezing was discernible from that of voluntary stopping when assessed using a virtual "gait" paradigm while lying down and navigating a virtual environment by using a set of foot pedals [30]. This research provides positive support, but little work has been done to identify how brain dynamics during freezing are distinct from those during voluntary stopping while walking using ambulatory EEG.

In our study, to discern the neurophysiological differences between freezing and voluntary stopping episodes, we conducted an experiment built upon the time up-and-go (TUG) protocol [31]. The TUG protocol consists of a sequence of sit-to-stand, walking, turning, and stand-to-sit tasks, each of which can be affected by freezing, especially when performed as a sequence [32]. In our study, we further added a condition of "voluntary stopping", in which the participants reacted to the verbal instruction to voluntarily "stop" while performing the TUG task. We tracked the EEG dynamics of patients with PD before and during FOG episodes and during voluntary stopping. Contrasting the signature of freezing with that of voluntary stopping could significantly help pave the way towards more effective therapeutics that accurately predict FOG events while excluding potential false-positives associated with voluntary stopping.

We hope that our findings will provide a potential avenue for therapeutic prediction and alleviation of freezing episodes in patients with PD and promote exploration of voluntary stopping in the gait cycle by characterising the EEG signatures, as the identification of these movement intentions could be very useful in motor rehabilitation processes.
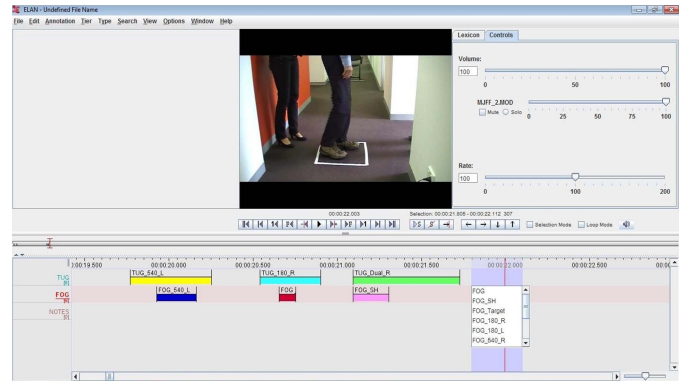


Fig. 1. The researcher used ELAN software to tag the events in each recording.

## II. MATERIALS AND METHODS

### A. Subjects

In this study, seventeen (17) patients aged $64 \pm 7.25$ years from the Parkinson's Disease Research Clinic at the Brain and Mind Centre, University of Sydney, were identified by using the score for item 3 of the self-reported FOG Questionnaire (FOGQ), which was further confirmed by specialist review. Consistent with our previous studies [19], [33], all patients satisfied the UK Parkinson's Disease Society Brain Bank (UKPDSBB) criteria, had a Mini-Mental State Examination (MMSE) score $\geq 24$ and were deemed unlikely to have dementia or major depression according to DSM-IV criteria by the judgement of neurologist Simon J. G. Lewis. These participants had varying severity and frequency of freezing, with a mean Unified Parkinson's Disease Rating Scale III stage when "off" of $40.10 \pm 12.21$ and a mean Hoehn and Yahr stage when "off" of $2.34 \pm 0.73$. This study was approved by The University of Sydney Human Research and Ethics Committee, and written informed consent was obtained.

### B. Experimental Design

All patients underwent a structured series of video-recorded TUG tasks while in their practically defined off state (having withdrawn from PD medication overnight for a minimum of 12 hours). All TUG tasks started in a seated position on a chair, from which patients walked along the centre of a large open corridor. A target box (0.6 m × 0.6 m) located six metres (6 m) from the chair was marked on the floor with white tape, and turning movements were performed in this box. A TUG task involved a 180° or 540° turn within the box and a return to the starting chair. It was performed with counterbalanced turns towards the patient's left or right side. Furthermore, the videos were independently reviewed, and FOG episodes were scored by two experienced clinical researchers. They used a tagging software program called ELAN to tag time points during the video, as shown in Fig. 1. After tagging the time points for the start of EEG recording and each FOG episode, the output was exported to Microsoft Excel, and the event timestamps were carefully added to the EEG data manually.

Our experimental paradigm consisted of two types of TUG tasks: a standard TUG task to trigger FOG and a TUG task with a voluntary stopping component in which "stop" or "walk" verbal instructions were provided by the investigators
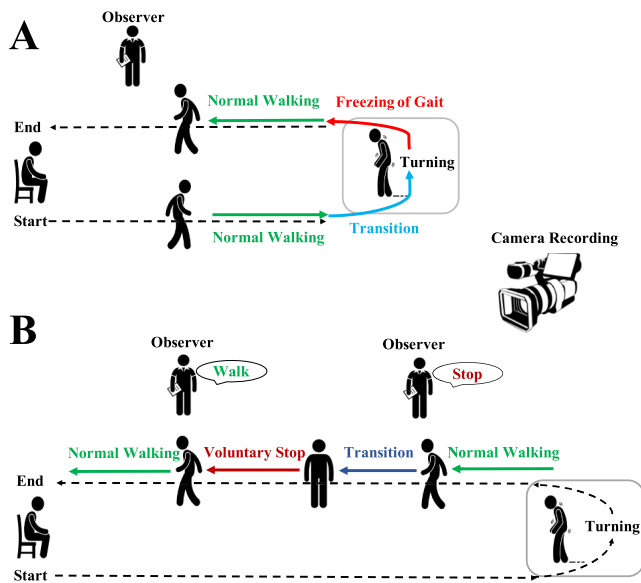
**Fig. 2.** Experimental protocol of the TUG tasks. (A) Standard TUG task. (B) TUG task with a voluntary stopping component with verbal instructions to "stop" and "walk" for assessing voluntary stopping.

TABLE I
PARTICIPANT-BASED COUNT OF FOG AND VOLUNTARY STOPPING TRIALS

| Subject No. | Number of FOG Trials | Number of Voluntary Stopping Trials |
|---|---|---|
| 1 | 8 | 3 |
| 2 | 8 | 4 |
| 3 | 1 | 0 |
| 4 | 33 | 0 |
| 5 | 2 | 3 |
| 6 | 5 | 3 |
| 7 | 1 | 6 |
| 8 | 11 | 4 |
| 9 | 8 | 0 |
| 10 | 23 | 0 |
| 11 | 0 | 5 |
| 12 | 24 | 6 |
| 13 | 0 | 3 |
| 14 | 15 | 0 |
| 15 | 1 | 1 |
| 16 | 1 | 6 |
| 17 | 12 | 4 |



**Fig. 3.** Diagram of the EEG preprocessing and analysis scheme.

to guide voluntary walking or stopping. For the standard TUG task (Fig. 2A), patients performed a series of timed TUG tasks on a standardised course to evoke FOG events [32]. Each FOG trial consisted of three epochs. Specifically, we defined a "normal walking" epoch as a 2-s period in which the PD patient walked normally with no cessation. In contrast, a "transition" epoch was the 2-s period before a freezing episode. Even though previous studies have examined a transition period of 5 s before freezing episodes [19], [33], we considered a 2-s transition period. This shorter transition period was chosen because it is anticipated to have more clinical utility, as the change in gait parameters is more pronounced one or two seconds prior to a freezing episode. Furthermore, studies have shown that the timing of gait rehabilitation methods should be optimised to ensure that performance is not hampered due to increased cognitive load [34], [35]. Finally, a "FOG" episode was defined as an involuntary stop and was identified as the 2-s period from when a patient experienced an unwanted cessation in their normal stride.

For the TUG with a voluntary stopping component with verbal instructions to "stop" and "walk" (Fig. 2B), a target box (0.6 m × 0.6 m) more than 10 m from the chair was marked on the floor with white tape, and turning movements were performed in this box. To promote voluntary stopping of the patients, the observer said the word "stop", and the patients were required to stop immediately. In the next 5-10 s, the observer said the word "walk", and the subjects were asked to start walking immediately. These voluntary stopping trials also consisted of three epochs. More specifically, we defined a "normal walking" epoch as a 2-s period in which the patient walked normally without cessation. A "transition" epoch was identified as the interval between giving a "stop" instruction and the time point when the patient physically stopped walking. A "voluntary stopping" episode was identified as the 2-s epoch beginning when the patient physically stopped walking.

Although the investigators desired to conduct an equal number of both TUG tasks, the actual number was variable and greatly dependent on the participant's health and ability to carry out the experiment. The investigators took great care to maintain each participant's wellbeing throughout the experiment. Therefore, the numbers of FOG and voluntary stopping trials were not the same. Table I provides details of the numbers of FOG and voluntary stopping trials for each participant.

### C. Data Recording and Analysis

Each patient wore a wearable BioSemi Active-Two system with 32 Ag-AgCl electrodes to record the EEG signals. The 32-channel electrodes (Fp1, Fp2, F7, F3, Fz, F4, F8, FT7, FC3, FCz, FC4, FT8, T7, C3, Cz, C4, T8, TP7, CP3, CPZ, CP4, TP8, P7, P3, Pz, P4, P8, O1, Oz, O2, A1, and A2) used the International 10–20 system locations to maintain a standard clinical setting, and the A1 and A2 electrodes were used as the reference channels. Before calibrating the electrodes, the patient's skin under the reference electrodes was washed with 70% isopropyl alcohol. The EEG signals were recorded at a sampling rate of 500 Hz with 16-bit quantisation.

### D. EEG Preprocessing

The EEG data were analysed with the EEGLAB toolbox [36] in MATLAB R2016a. As shown in Fig. 3, the raw EEG signals were initially preprocessed by a 1-30-Hz bandpass filter to remove line noise, low-frequency noise and high-frequency noise. Removing artefacts, such as eye movement and muscle activity, is crucial, as they can adversely

affect further processing steps. For artefact rejection, eye movement contaminants in the EEG signals were identified by visual inspection and manually removed.

Additionally, artefacts were removed by the Automatic Artifact Removal (AAR) [37], [38] plug-in for EEGLAB, which integrates many state-of-the-art methods for automatic correction of ocular and muscular artefacts in the EEG signals. This toolbox uses blind source separation to decompose the EEG data into several spatial components before automatically removing artefact-related components. It then reconstructs the EEG signal by using the non-artefactual components. Afterwards, the FOG and voluntary stopping trials were extracted for further analyses, and a time-warping method was used to measure latencies.

In this study, a total of 178 FOG episodes and 54 voluntary stopping episodes were analysed. In the standard TUG task, only the trials that had freezing episodes were used for further processing. In particular, these 178 FOG episodes were extracted from both TUG tasks, 74 of which occurred during turning, while 104 occurred during the normal stride.

### E. EEG ERSP Analysis

The FOG and voluntary stopping epochs were extracted from the continuous EEG signals, and each epoch contained the sampled EEG data from $-2000$ ms to $4000$ ms with the stimulus onset at $0$ ms. To investigate brain dynamics during the FOG and voluntary stopping episodes and the subsequent motor responses, each epoch was separately transformed into a time-frequency representation by using an event-related spectral perturbation (ERSP) routine [39], which is a time-frequency analysis performed to transform time-domain signals into the spectral-temporal domain to characterise the event-related frequency changes by using the short-time Fourier transform (STFT).

To compute the ERSP for each trial, spectra prior to the event onset are considered the baseline spectra for that trial. The mean of the baseline spectra (in dB) is subtracted from the spectral power after event onset to visualise the spectral "perturbation" from the baseline. The mean normal walking log power spectrum (in dB) of the optimal epochs, which was used as the reference (baseline) value, was subtracted from each estimated spectrum. The ERSP is derived by computing the power spectrum over a sliding latency window and then computing the average across all the trials. Therefore, for n trials, if $F_k(f, t)$ is the spectral estimate of trial $k$ at frequency $f$ and time $t$, the ERSP is given by

$$ERSP(f, t) = \frac{1}{n} * \sum |F_k(f, t)|. \qquad (1)$$

In EEGLAB, $F_k(f, t)$ is calculated by using the STFT [40]. The relative power at a particular frequency and latency is indicated by the colour of the corresponding pixel in the ERSP image. Therefore, the preprocessed time-series EEG data were transformed into the frequency domain by a 256-point fast Fourier transform with Welch's method. Specifically, 90-s spans of data were analysed with a 256-point moving window with a 128-point overlap. Windowed data were extended to 512 points by zero-padding to calculate power spectra, yielding an estimation of the power spectra with 60 frequency bins from 1 to 30 Hz.

In this study, the mean power spectra, including the delta (1-3.5 Hz), theta (4-7.5 Hz), alpha (8-12.5 Hz), and beta (13-30 Hz) bands, from normal walking and the transition to FOG or voluntary stopping were vertically stacked. We considered the event-related spectral perturbation at the four important electrodes (Fz – supplementary motor area, Cz – primary motor area, P4 – navigational movement area, and O1 – primary visual receiving area) as reported in an earlier study [19]. Moreover, Handojoseno et al. [20] observed that P4 channel data were the most crucial feature for detecting FOG episodes. Furthermore, the left-hemisphere (5 channels - F3, FC3, C3, CP3, and P3) and right-hemisphere (5 channels - F4, FC4, C4, CP4, and P4) brain areas were also considered to explore event-related band power dynamics that accompanied the transition of power changes before and after the FOG and voluntary stopping episodes.

### F. Statistical Analysis

The ERSPs for normal walking, the transition to FOG and the transition to voluntary stopping were compared using paired t-tests with a Bonferroni correction, which is a multiple-comparison correction used when several dependent or independent statistical tests are being performed simultaneously. Independent t-tests were performed to compare the ERSPs between the FOG and voluntary stopping episodes. The significance level was set at $p < 0.05$, and the statistical analysis was performed in MATLAB (R2016a).

## III. RESULTS

### A. Event-Related Band Power Dynamics During FOG in the TUG Trials

The two-dimensional images in Fig. 4 show the ERSPs of the frontal, central, parietal, and occipital channels for patients with PD accompanied by FOG. As shown in Fig. 4, the mean EEG power spectra before and after the onset of freezing at the Fz, Cz, P4 and O1 electrodes are presented. In particular, the ERSP at the Cz electrode showed a decreased EEG power spectrum during the transition period relative to normal walking and an increased EEG power spectrum in the transition period relative to FOG episodes.

Furthermore, we compared the different periods during FOG episodes, as shown in Fig. 5. Compared with those during normal walking, the EEG alpha power band and a portion of the beta power band in the transition period were significantly elevated at the Cz and O1 electrodes (p < 0.05). The ERSP changes during the transition period and at the onset of FOG showed partial increases in the beta power band at the Fz and P4 electrodes, significantly lower theta and alpha power bands early in the time interval at the Fz, Cz, P4 and O1 electrodes, and partial increases in the EEG power spectrum late in the time interval at the P4 and O1 electrodes (p < 0.05) during the transition period relative to the FOG episodes.

### B. Event-Related Band Power Dynamics Between Voluntary Stopping and FOG Episodes During the TUG Trials

The two-dimensional images in Fig. 6 show the ERSPs of the voluntary stopping (Fig. 6A) and FOG episodes during the TUG task (Fig. 6B) at the frontal, central, parietal, and occipital channels for patients with PD accompanied by FOG.
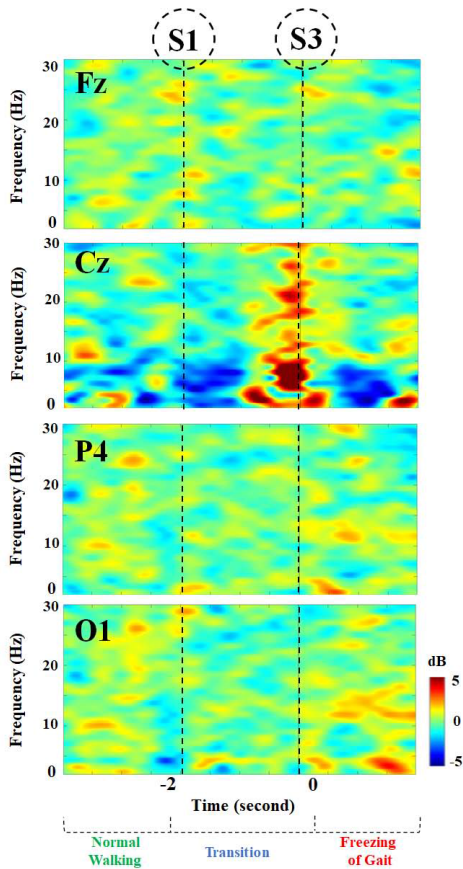
**Fig. 4.** Event-related band power dynamics during FOG episodes while performing the TUG task. S1 denotes the timing from normal walking to the transition period, and S3 denotes the timing from the transition period to FOG. ERSP changes from normal walking ($< -2$ s) to the transition ($-2$ s to 0 s) and FOG ($> 0$ s) at four electrodes (Fz, Cz, P4 and O1).
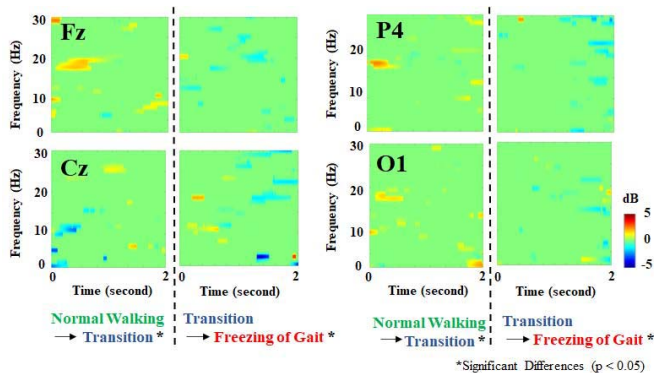


**Fig. 5.** Comparisons of the ERSP differences between the normal walking and transition periods (left column) and the transition period and FOG episode (right column) at four important electrodes (Fz, Cz, P4 and O1).

Regarding the voluntary stopping episodes during the TUG task (Fig. 6), a globally increased EEG power spectrum in the delta, theta, alpha and beta bands was observed in the transition period relative to normal walking. Furthermore, a partially decreased EEG power spectrum was observed during voluntary stopping relative to the transition period, and in particular, significantly reduced delta and beta power bands were observed during voluntary stopping at the Cz electrode.

We compared the ERSP differences between the FOG and voluntary stopping episodes while performing the TUG task

during the normal walking, transition, and freezing/voluntary stopping periods at the four important electrodes (Fz, Cz, P4, and O1), as shown in Fig. 6C. Our results showed significantly enhanced delta, theta, alpha and beta ERSPs in the voluntary stopping episodes relative to the FOG episodes during the normal walking and transition periods ($p < 0.05$). The ERSP in the transition period preceding voluntary stopping demonstrated an increased power spectrum compared with that of the FOG episodes. More importantly, the ERSP during voluntary stopping showed a significantly decreased EEG power spectrum compared with that during freezing ($p < 0.05$), and in particular, a distinctly reduced delta and low-beta EEG power spectrum was noted at the Cz electrode.

To render the number of FOG and voluntary stopping trials comparable, we studied the ERSPs of voluntary stopping and FOG trials after removing all the FOG episodes that occurred during turning. There were 119 FOG trials remaining after all the FOG trials at turning were removed. Fig. 7 shows the ERSPs of voluntary stopping (Fig. 7A) and FOG (Fig. 7B) trials during the TUG task without the FOG during turning at the frontal, central, parietal, and occipital channels for the PD patients. A comparison between voluntary stopping and FOG trials without the turning FOG during normal walking, transition, and FOG or voluntary stopping periods at the Fz, Cz, P4 and O1 electrodes is shown in Fig. 7C. The observed results were similar to the ERSP results in which FOG trials at turning were also included. These results also showed enhanced delta, theta, alpha and beta ERSP in voluntary stopping trials compared with the ERSP in FOG trials during the normal walking and transition periods ($p < 0.05$). The ERSP in voluntary stopping trials showed a similarly increased power spectrum during the transition period compared with that in FOG trials. The results also showed a decreased power spectrum during a voluntary stop compared with FOG ($p < 0.05$). The ERSP at the Cz electrode also showed a distinctly reduced delta and low-beta EEG power spectrum during the voluntary stop compared with that during freezing.

### C. Brain Hemisphere Power Dynamics Between the Voluntary Stopping and FOG Episodes

Fig. 8 displays the results of the average EEG power spectra in the left and right hemispheres for the voluntary stopping and FOG episodes during the TUG task. For the voluntary stopping episodes during the TUG task, as shown in Fig. 8A, a partial decrease in the delta power and an increase in the beta power were observed in the left and right hemispheres during the transition period compared with those during normal walking. Furthermore, the ERSP maintained decreased delta and low-beta power and increased high-beta power during a voluntary stop in the left and right hemispheres. For FOG episodes during the TUG task, as shown in Fig. 8B, no significant change in the ERSP was noted except for a slight increase in the alpha power during freezing.

The differences in the brain hemisphere power dynamics between the voluntary stopping and FOG episodes during the TUG tasks are shown in Fig. 7C. Specifically, our results demonstrated that the EEG power spectrum during the transition was significantly higher in the beta band and slightly lower in the delta band during the voluntary stopping episodes
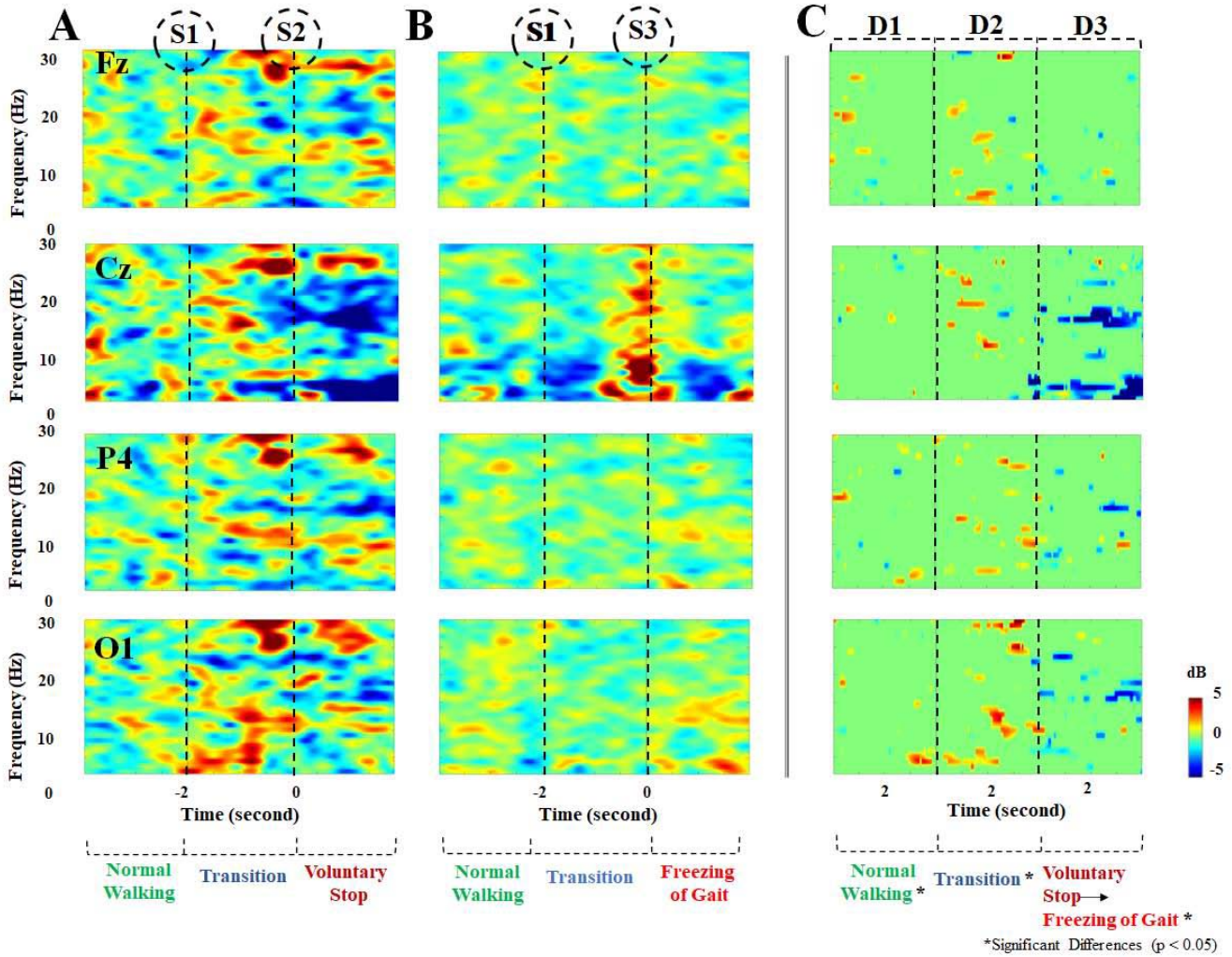
Fig. 6. Event-related band power dynamics between the voluntary stopping and FOG episodes during the TUG task. (A) ERSP changes during the voluntary stopping episodes in the normal walking ($< -2$ s), transition ($-2$ s to 0 s), and voluntary stopping ($> 0$ s) periods at four electrodes (Fz, Cz, P4 and O1). (B) ERSP changes during the FOG episodes in the normal walking ($< -2$ s), transition ($-2$ s to 0 s), and FOG ($> 0$ s) periods at four electrodes (Fz, Cz, P4 and O1). (C) Comparisons of the ERSP differences between the voluntary stopping and FOG episodes during the TUG task at four important electrodes (Fz, Cz, P4 and O1). S1 denotes the timing from normal walking to the transition period, S2 denotes the timing from the transition period to voluntary stopping, S3 denotes the timing from the transition period to FOG, D1 denotes the difference during normal walking, D2 denotes the difference during the transition period, and D3 denotes the difference between the voluntary stopping and FOG episodes.

than during the FOG episodes ($p < 0.05$). Our results showed a significantly lower power in the delta to low-beta bands during the voluntary stopping period than during the FOG period ($p < 0.05$). Moreover, we also noted a significantly higher high-beta power during the voluntary stopping period than during the FOG episode ($p < 0.05$).

## IV. DISCUSSION

This study examined the ERSPs during voluntary stopping and freezing episodes using a revised TUG task with a voluntary stopping protocol. In this study, the brain dynamics during the FOG and voluntary stopping episodes were analysed by employing an ERSP routine. However, there have been several recent advances in EEG analysis methods [41]–[43]. Neural dynamics have been studied using EEG microstate analysis [42], a spatio-temporal method that segments signals into several quasi-stable classes. However, the microstate analysis method requires higher electrode densities to obtain reliable results [41]. Another novel EEG source imaging method,

called the WPESI, was found to achieve a favourable outcome in identifying seizure onset zones in epilepsy patients [43]. Future studies may employ such advanced analysis methods to improve the characterisation of FOG episodes.

Our findings demonstrated the potential of ERSP analysis for identifying voluntary initiation and termination of the gait cycle. One key finding of this study was the increase in the EEG power in the central brain area before the onset of freezing episodes relative to that of normal walking. This finding resembles that of a recent study [19] that calculated the mean power spectral density, as shown in Table II. Interestingly, both studies identified an increase in the EEG beta power despite the application of different power measures and transition period definitions.

In our study, the ERSP changes in all 178 FOG episodes were individually analysed to evaluate the statistical significance of the results. Each FOG episode showed a similar increase in power in the central brain area before the onset of freezing. Another key observation was that the ERSP
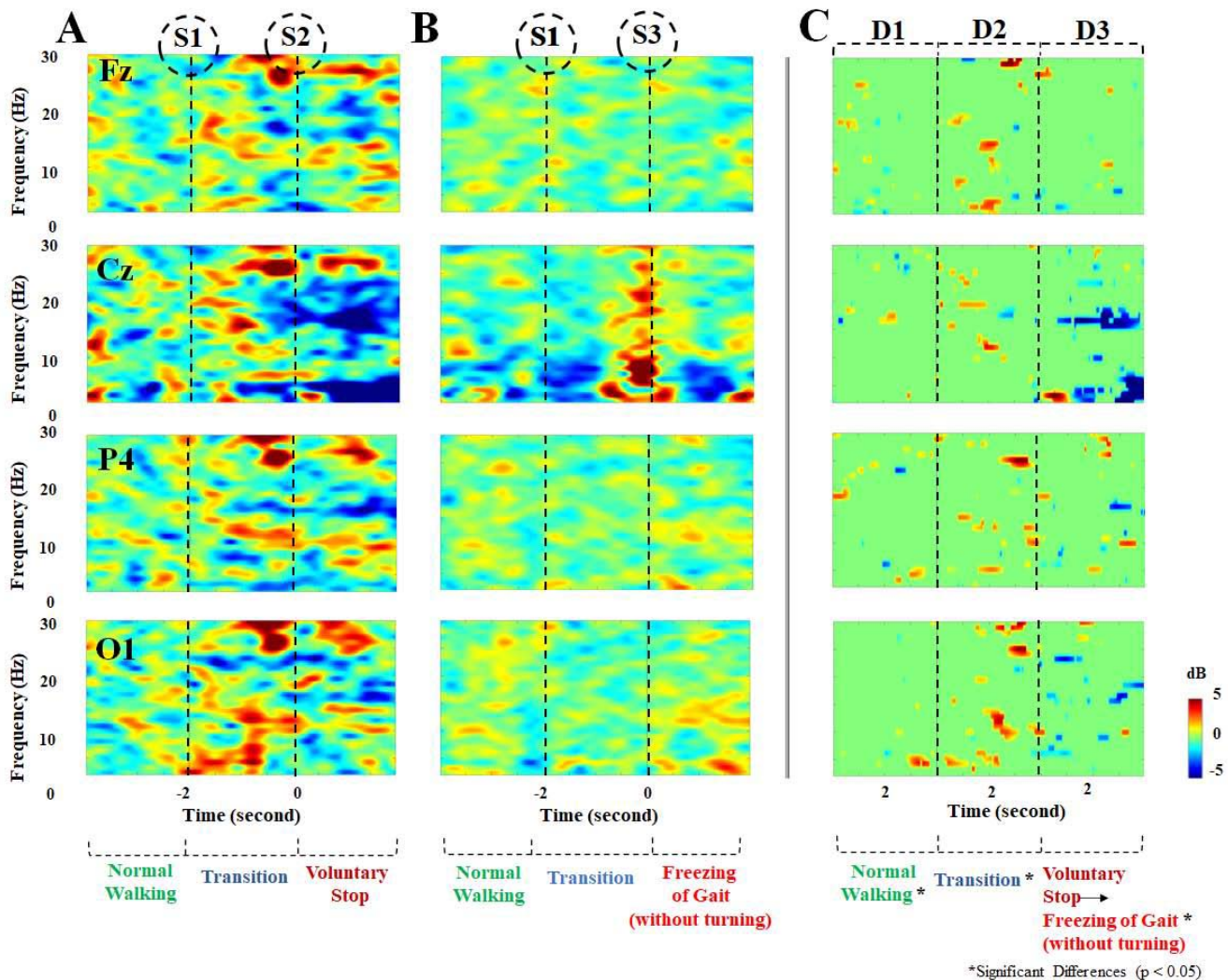
Fig. 7. Event-related band power dynamics between the voluntary stopping and FOG trials during the TUG task in which all the FOG episodes at turning were removed. (A) ERSP changes during the voluntary stopping episodes in the normal walking ($< -2$ s), transition ($-2$ s to $0$ s), and voluntary stopping ($> 0$ s) periods at four electrodes (Fz, Cz, P4 and O1). (B) ERSP changes during the FOG in which all the FOG episodes at turning were removed in the normal walking ($< -2$ s), transition ($-2$ s to $0$ s), and FOG ($> 0$ s) periods at four electrodes (Fz, Cz, P4 and O1). (C) Comparisons of the ERSP differences between the voluntary stopping and FOG in which all FOG episodes at turning were removed during the TUG task at four important electrodes (Fz, Cz, P4 and O1). S1 denotes the timing from normal walking to the transition period, S2 denotes the timing from the transition period to voluntary stopping, S3 denotes timing from the transition period to FOG, D1 denotes the difference during normal walking, D2 denotes the difference during the transition period and D3 denotes the difference between the voluntary stopping and FOG episodes.

changes associated with voluntary stopping episodes showed an elevated high-beta power at the Fz, Cz, P4, and O1 electrodes. These changes were verified in each voluntary stopping episode, and every episode showed a significantly increased high-beta power at these four electrodes. In addition, decreases in the EEG power were observed in the frontal, central, parietal and occipital areas during the voluntary stopping compared with the FOG episodes.

## A. FOG Episodes Related to EEG Power Dynamics in the Central Area

Tracking and identifying FOG episodes by characterising their EEG signatures may provide a potential method for therapeutic prediction and alleviation of freezing episodes in patients with PD. Our study presented a novel finding that the transition from normal walking to freezing was associated with a significant increase in the EEG power in the central brain area. This central sensorimotor brain region, which facilitates motor processing, has great anatomical significance, as the foot representation areas are in the somatotopic organisation of the motor cortex [44]. Our results showed an increase in delta and theta activity during the transition to freezing in the central area. The enhanced EEG power may indicate that the brain's inhibitory processes are activated by freezing episodes, mainly in the central area.

Furthermore, clinical studies have shown that freezing behaviour in PD is associated with a paroxysmal increase in theta oscillations (5 - 7 Hz), known as "trembling in place" [45]. The changes observed in the EEG power spectrum in the theta band during freezing may be due to mechanical oscillations transmitted to the scalp electrodes. Notably, the increase in the theta power was unlikely to be due to global motor interference, as we observed a significant increase in the theta power only in the central area. Perhaps a more
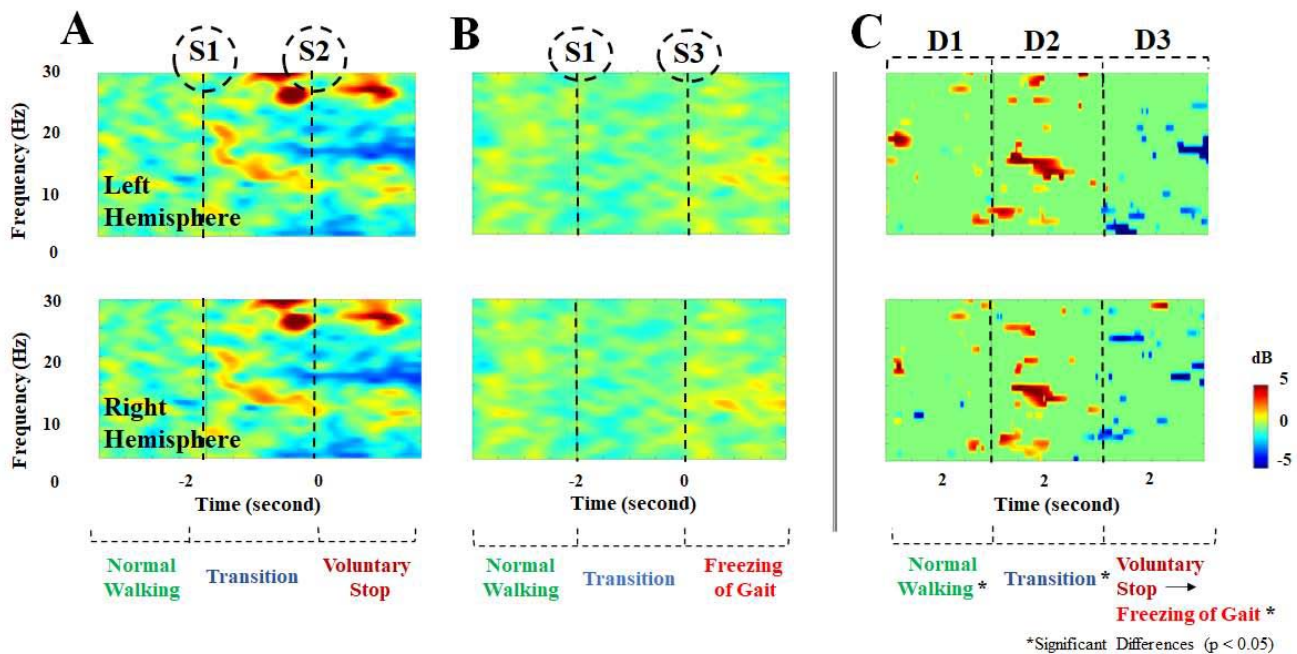
Fig. 8. Brain hemisphere power dynamics during voluntary stopping and FOG episodes in the TUG task. (A) ERSP changes during the voluntary stopping episodes in the normal walking ($< -2$ s), transition ($-2$ s to 0 s), and voluntary stopping ($> 0$ s) periods in the left and right hemispheres. (B) ERSP changes during FOG episodes in the normal walking ($< -2$ s), transition ($-2$ s to 0 s), and FOG ($> 0$ s) episodes in the left hemisphere. (A3) Comparisons of the ERSP differences between the voluntary stopping and FOG episodes in the left and right hemispheres. (C) Comparisons of the ERSP differences between the voluntary stopping and FOG episodes in the left and right hemispheres. S1 denotes the timing from normal walking to the transition period, S2 denotes the timing from the transition period to voluntary stopping, S3 denotes the timing from the transition period to FOG, D1 denotes the difference during normal walking, D2 denotes the difference during the transition period, and D3 denotes the difference between the voluntary stopping and FOG episodes.

acceptable explanation is that a dysfunctional neuronal circuit in subcortical brain structures drives the creation of theta oscillations in patients with PD [46]. A similar mechanism was recently found to underlie the oscillations observed during FOG [19].

The results also showed that the beta activity in the central area was enhanced during this transition period. The change in the beta power may be associated with the facilitation of postural activities, including a tonic holding contraction and inhibition of voluntary movement [47]. Moreover, beta suppression is critical for the facilitation of continuous movement sequences [48], suggesting that high-beta activity may interface with anticipatory postural adjustments in preparation for stepping, which can facilitate excessive postural contraction of the lower limbs associated with FOG episodes [49].

### B. Acute Prediction and Detection of FOG Episodes

In previous studies, the transition period prior to FOG was defined as the time window of 5 to 1 s before the occurrence of freezing [19], [33]. However, this study analysed a shorter transition period of 2 s before freezing, which may have more clinical utility, as gait parameters usually change prior to freezing within a short time window. Compared with those of previous studies, the EEG power in this study showed similar changes at the Cz electrode but different changes at the O1 electrode in the transition period from normal walking, suggesting that the EEG in the occipital area may be susceptible to the preparation of freezing. In this study, considering a 2-s transition period to a FOG event, we observed an increase in the beta power in the central region of the brain, as with

the 5-s transition period, compared with normal walking. However, we also observed an increase in the alpha power in the central region, while an increase in the theta power was observed during the 5-s transition period compared with the normal walking period. When the 5-s transition period was compared with the normal walking period, increases in the alpha and beta power were observed in the parietal area; however, only a partial increase in the beta power was observed when the 2-s transition period was compared with the normal walking period. While an increase in only the beta power in the occipital area was observed when the 5-s transition period was compared with normal walking, we observed increases in both the alpha and beta power in the occipital region compared with the 2-s transition period to normal walking.

### C. EEG Power Dynamics Between Involuntary and Voluntary Stopping

Currently, few studies [19], [21] have highlighted the distinctions of different motor inhibition processes; thus, investigating brain dynamics under conditions of involuntary stopping (freezing) and voluntary stopping can provide unique insights. Our results showed that the voluntary stopping period was associated with a significantly decreased EEG power spectrum compared with that in the freezing period, and a distinctly different pattern in the delta and low-beta power was particularly observed in the central area. These suppressions may reflect motion preparation and execution [50] as well as EEG oscillatory patterns, reflecting the process of inhibitory control in the brain [51], [52], which controls the cessation of foot movement when patients hear "stop" cues during TUG trials.

TABLE II
EEG DYNAMICS DURING THE TRANSITION TO FOG

| EEG Pattern | Frequency | Observation at Brain Cortices | | |
|---|---|---|---|---|
| | | Central | Parietal | Occipital |
| Power spectral density (PSD) with a 5-s transition [19][a] | $\delta$ | N/A | N/A | N/A |
| | $\theta$ | ↑ | N/A | N/A |
| | $\alpha$ | N/A | ↓ | N/A |
| | $\beta$ | ↑ | ↑ | ↑ |
| ERSP with a 2-s transition (Our findings)[b] | $\delta$ | N/A | N/A | N/A |
| | $\theta$ | N/A | N/A | N/A |
| | $\alpha$ | ↑ | N/A | ↑ |
| | $\beta$ | ↑ | ↑ | ↑ |

[a] The transition period, defined as 5 s before a FOG episode.
The extracted period of normal walking is 5 s.
[b] The transition period, defined as 2 s before a FOG episode.
The extracted period of normal walking is 2 s.
↑ ↓ The up and down arrows represent an increase and a decrease, respectively
EEG power in the transition period compared
with the normal walking period.

In fact, the voluntary stopping task in our TUG task with the voluntary stopping component is similar to the stop-signal paradigm, wherein a participant engaged in a task stops their primary task when presented with a signal to stop [23]. As with the stop-signal paradigm, voluntary stopping during the TUG task may also involve initiation and inhibition. The transition period in the voluntary stopping episode is similar to response inhibition, in which the subject is required to stop walking after initiating movements quickly. Regarding the transition period, our results showed increased EEG power in the voluntary stopping episodes compared with the FOG episodes. This strengthening of the EEG power indicates an effective preparation stage for response inhibition [46], whereas a low EEG power spectrum during freezing may involve incomplete or ineffective inhibitory control over some movement options.

Our findings demonstrate distinct brain dynamics during freezing and voluntary stopping episodes, which can be instrumental in gait rehabilitation, which generally employs compensatory methods to preserve and improve the activity of the alternative neural circuits that will aid gait in PD patients. These compensatory strategies include providing cues to prompt movement or manipulating the attention allocation to prevent movement breakdown [53]. In recent years, wearable sensing technology has been employed to trigger an intelligent provision of cues during gait [54], [55], which has resulted in the development of several FOG detection algorithms [19]–[21]. However, the efficacy of this technology-based compensatory system also heavily relies on accurately discriminating FOG episodes from voluntary stopping episodes to reduce false-positives related to voluntary stopping. We are in the process of developing a robust FOG detection model that accurately identifies freezing episodes and discriminates freezing from voluntary stopping. Table III shows some preliminary results regarding the accuracy of several classical machine learning algorithms (SVM, KNN and Random Forest) in discriminating the transition to freezing from the transition to voluntary stopping with approaching 80% accuracy. The identified EEG features are power spectral at the Fz, Cz, P4 and O1 channels calculated using Welch's periodogram method on each transition period of 2s for a range of delta, theta, alpha, beta, and gamma frequencies from 1 to 45 Hz. The 5-fold cross-validation is implemented to train and test the classifier algorithms.

TABLE III
CLASSIFICATION RESULTS OF TRADITIONAL MACHINE LEARNING ALGORITHMS IN DISCRIMINATING THE TRANSITION TO FREEZING FROM THE TRANSITION TO VOLUNTARY STOPPING

| Classifier | Accuracy | F1 score | Sensitivity | Specificity |
|---|---|---|---|---|
| Linear SVM | 68.09% | 68.30% | 68.42% | 66.21% |
| Kernel SVM | 79.44% | 79.32% | 84.12% | 73.80% |
| KNN (K = 5) | 73.21% | 72.11% | 88.49% | 54.36% |
| Random Forest | 73.02% | 72.94% | 79.69% | 66.91% |

## V. CONCLUSION

This study investigated the brain dynamics of FOG and voluntary stopping episodes using EEG data collected from patients with PD accompanied by FOG. Our findings highlighted that FOG episodes were associated with abnormal EEG dynamics and that voluntary stopping could be discriminated from FOG episodes. Comparing the transition to the freezing period with the freezing period itself, our findings show that freezing episodes are associated with significantly increased theta and alpha band power within the central and occipital areas. Furthermore, the EEG power significantly decreased during the voluntary stopping period compared with the FOG period. Our results provide novel insights into the rapid transition dynamics underlying the phenomenon of FOG and may provide a potential means for the therapeutic prediction and alleviation of freezing episodes in susceptible patients. These findings are very useful for the development of future technologies that predict FOG episodes, as they suggest that voluntary stopping will not activate false positives, allowing for the accurate detection of freezing.

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