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Article

Cross-Task Differences in Cortical Activations for Dynamic Balance in Neurotypical Adults

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Abstract: Although significant progress has been made in understanding the cortical correlates underlying balance control, these studies focused on a single task limiting the ability to generalize the findings. Different balance tasks may elicit cortical activations in the same regions but show different levels of activation because of distinct underlying mechanisms. In this study, we instructed twenty young, neurotypical adults to maintain standing balance while the standing support surface was either translated or rotated and investigated the differences in cortical activations between these two widely used tasks using whole head electroencephalography (EEG). Additionally, we investigated whether transcranial magnetic stimulation could modulate these cortical activations. We found higher delta and lower alpha relative power over the fronto-central region during the platform translation task when compared to the platform rotation task suggesting greater engagement of attentional and sensory integration resources for the former. Continuous theta burst stimulation (cTBS) over the supplementary motor area (SMA) significantly reduced delta activity in the fronto-central region but did not alter alpha activity during the platform translation task. Our results provide a direct comparison of neural activations between two commonly used balance tasks and are expected to lay a strong foundation for designing neurointerventions for balance improvements with effects generalizable across multiple balance scenarios.

Keywords: balance; perturbation; sway reference; supplementary motor area; cTBS; EEG

1. Introduction

The control of balance requires a complex interplay between sensory information arising from visual, vestibular, and somatosensory systems for generation of motor commands to maintain an upright stance [1]. Balance control predicts function and engagement of individuals in activities of daily living (ADLs) [2–4]. Poor balance control, as it happens due to aging or neurological disorders, is a predictor of falls [5–8]. For neurotypical adults, standing balance is a seemingly trivial task, controlled primarily by subcortical brain structures and the spinal cord with very limited cortical involvement [9]. Several studies have suggested the involvement of cortex [10] when the stance is challenged through blindfolding the participant [11], using a single support [12,13], standing on an unstable platform [14], or standing on a platform capable of making unexpected translations or rotations [15].

Activations across several fronto-parietal regions [16–20], including anterior cingulate, supplementary motor area (SMA), and posterior parietal cortices [21–24], are commonly reported, yet causal relationships are not completely understood [25]. Similar tasks often report the same regions of interest but may demonstrate different levels of activation. Researchers investigating postural stability often use a force plate capable of administering a translation of the standing

platform (perturbation task; PT) or a force plate that is sway-referenced (sway reference task; SRT) in reference to deviations in subject's center of pressure [26]. The perturbation task (PT) is associated with a characteristic evoked potentials observed in the electroencephalographic (EEG) activity following the perturbation but preceding the initiation of a functional balance task [27]. These perturbation-evoked potentials originate from fronto-central brain regions such as anterior cingulate or SMA [21,22]. The characteristics of these potentials such as the amplitude and latency are known to be affected by novelty [24], predictability [28,29], attention [30], and speed [31] of the perturbation, observable on a single trial basis [24,32], and precedes postural instability and stepping to prevent imminent falls [23]. For the sway reference task (SRT), on the other hand, these evoked potentials are smaller in magnitude, but can be identified during the task [33]. PT and SRT differ in fundamental mechanisms underlying balance control [34]. Platform translation is an imposed mechanical perturbation that can be considered an error signal unrelated to ongoing stance. However, sway-referencing the platform results in sensory manipulation and alters sensory feedback regarding motor outputs during ongoing control such that their effects are a function of the action of the participant. A smaller evoked response during SRT when compared with PT suggests that the cortical response is stronger in case of PT. None of the studies have performed a direct comparison of fronto-central cortical activation levels between the PT and SRT tasks. Such knowledge will lay a foundation for designing neurointerventions for balance improvements with effects generalizable across multiple tasks.

Furthermore, understanding the certainty of causal influence of cortical activation on the control of balance during challenging conditions is important for rehabilitation researchers. High frequency repetitive transcranial magnetic stimulation (cTBS) has been used for inducing virtual lesions of brain regions and understanding its effect on balance control [35]. For example, our earlier work found that disruption of (SMA) using inhibitory cTBS altered EEG band power in lower frequency bands within brain areas involved in the control of balance during SRT, thus confirming the role of SMA in this behavior [18]. The effects of repetitive cTBS over SMA on the fronto-central brain activity during PT are yet to be known.

In this study, we investigated differences in cortical activation measured using EEG across two commonly used balance tasks, the perturbation task and the sway reference task in neurotypical adults. We expected common EEG sources of brain activation across PT and SRT tasks but differences in their activation levels. Considering the known disruptive effects of cTBS over SMA on rhythmic synchronous cortical oscillations measured non-invasively using EEG during the SRT task, we expected that cTBS over SMA will alter EEG band power within the frontocentral brain regions during PT in neurotypical adults.

2. Materials and Methods

Twenty healthy, right-handed young adults (age: 26.0 ± 3.4 years; 8 females; height: 168.0 ± 11.8 cm; weight: 66.7 ± 13.8 kg, mean $\pm$ standard deviation (SD)) provided written, informed consent for participation. Two groups ($n = 10$, 4 females) were randomly selected to receive cTBS over SMA (cTBS_{SMA}) or a sham control (cTBS_{SHAM}). No participants reported history of balance, neurological, musculoskeletal, cardiovascular, or vestibular disorders, and were screened with the Physical Activity Readiness Questionnaire (PAR-Q) and TMS Adult Safety Screening Questionnaire. The Committee for the Protection of Human Subjects at the University of Houston approved this study.

Instrumentation

Electroencephalography (EEG):

Whole-scalp EEG with 64 active channel electrodes (Brain Products GmbH, Germany; 1000 Hz) was recorded at rest and during the balance tasks. An elastic cap constrained the movement of the electrodes during the balance task. A modified international 10-20 system was used, where GND and REF were attached to the earlobes, and replaced by T7 and T8 electrodes. However, four electrodes were repurposed for electrooculography (EOG), where the electrodes were placed around the participants' eyes, to remove eye artifacts during EEG preprocessing [18,31].

Computerized dynamic posturography (CDP):

A standard, commercial CDP force platform (NeuroCom Balance Manager, Natus Medical Incorporated, Pleasanton, CA) was used for both balance tasks, as done previously [18,31]. During all posture tasks, subjects wore a safety harness to prevent falls or injury. The platform is equipped with a dynamic 45.72 cm x 45.72 cm dual force plate system. The ground reaction forces from under the feet of subjects were collected by four individual force transducers embedded within the force plate. Force platform data were collected at 100 Hz and processed by pre-installed software on a Windows-based desktop connected to the NeuroCom Balance Manager (Research module, NeuroCom software version 8.0, Natus Medical Incorporated, Pleasanton, CA). Our previous work has reported the analysis of center of pressure data during PT [31] and SRT [18]. An analog output signal of 5 V generated by the NeuroCom system was used to synchronize NeuroCom data with the EEG system [31].

Balance Tasks

Sway Reference Task (SRT):

Participants were instructed to perform the sway reference task with varying sensory conditions. The goal of this task was to maintain a quiet upright stance with eyes closed. They completed nine trials of 20 second durations each, where the platform was referenced to their sway with different gain settings. The orientation of the platform of the balance manager was adjusted with respect to the gravitational vertical by rotating it in the sagittal plane about an axis through the subject's ankle joint in some proportion (a preselected gain between -2 to +2) to the postural sway of the subject. The purpose of this task was to alter the relationships between postural sway and somatosensory inputs by randomly varying the gain of the support surface. We used a range of gains (-1.0, -0.4, 0, 0.4, 0.6, 1.0, 2.0) to expose subjects to different levels of postural difficulty. Subjects were not informed when the gain changed. These postural conditions allowed us to manipulate the difficulty of the postural control task progressively while concurrently monitoring variations in the EEG responses. Subjects were not allowed to practice at different gains of the sway-referenced support surface. The trials were continuous with a brief (<10 second) delay to save the data and begin the new trial, thus demarcating the start of each trial in the EEG and used in analysis.

Perturbation Task (PT):

Participants were instructed to maintain an upright stance with eyes closed during destabilizing postural perturbations. The perturbations were in the form of unexpected translation of the force platform upon which the subject stood. Six different perturbation conditions [31] were used with direction (backward and forward), displacement (3.17 cm and 6.35 cm), speed (7.93 cm/s and 15.88 cm/s), and period (400 ms and 800 ms) varying from condition-to-condition, randomized in order. Participants completed a total of eighteen discrete trials, 3 trials per perturbation condition. Each trial lasted for 5000 ms, which included 1000 ms of "pre-perturbation phase," 400 or 800 ms of "perturbation phase," and 3600 or 3200 ms of "post-perturbation phase." In the post-perturbation period, the force plate remained stationary at the translated position. The onset of perturbation occurred 1000 ms after the trial onset. Participants were not informed of the start of each trial, nor warned of perturbation onset. At the end of each trial, the platform translated back to the original position at 1.00 cm/s, which took 3500-6200 ms, and then the next trial was initiated after a brief (<10 s) delay to save the trial data. The effects of different perturbation characteristics have been studied in our previous work [31]. All trials were grouped together for analysis. To capture a naïve response, no practice session was provided before the experimental trials. EEG activity was recorded for all the trials.

Transcranial Magnetic Stimulation Procedures

We estimated the active motor threshold (aMT) by placing a figure-of-eight TMS coil (Magstim Super Rapid² stimulator; Magstim, Whitland, UK) tangential to the scalp, oriented at 45° from the midsagittal line, with the handle pointing backward, inducing a current in the postero-anterior direction. The hand motor region of the left primary motor cortex (M1) that is associated with the

right first dorsal interosseus (FDI) muscle was located using supra-threshold TMS pulses [36,37]. Electromyographic (EMG) activity in the FDI muscle of the right hand was recorded using a differential surface electrode (Bagnoli EMG system, Delsys, Natick, MA). The largest grip force exerted using the index finger and thumb on an instrumented force sensing handle over three trials was used as the maximum voluntary force (MVF) [38]. The aMT was determined as the TMS intensity that induced 200 μ V peak-to-peak motor evoked potentials (MEPs) in 5 of 10 trials in the FDI muscle during grip force exertion at 20% of MVF [39], using visual feedback. The aMT was estimated to be $52 \pm 5\%$ (mean $\pm$ SD) of the maximum stimulator output [18].

For each subject, we obtained high-resolution T1-weighted structural images [18] using a 3T Siemens Trio whole-body MR scanner (Erlangen, Germany) before the experiment. A three-dimensional (3D) brain was reconstructed from the MRI slices to display the cortical surface (Brainsight software, Rogue Research, Montreal, QC, Canada). The location of the left SMA was demarcated for each subject. We chose left SMA because of postulated functional asymmetry between motor areas with the dominant brain hemisphere playing a more important role in the selection of appropriate postural strategies [18]. The location of the left SMA was selected as the most medial part of the superior frontal gyrus, which was anterior and dorsal to the precentral gyrus [40–42]. Because SMA is located directly anterior to the leg representation of M1 at the same depth on the interhemispheric surface [43,44], the optimal coil position to evoke MEPs in the right tibialis anterior (TA) muscle was determined first while subjects were instructed to exert ~20% of maximum voluntary contraction of right TA [41,45]. The coil was then moved anterior in small increments, and the final SMA location was chosen 1 cm anterior from the point where there were no MEPs in the right TA. If needed, the coil position was slightly adjusted based on the anatomical target. For the virtual lesion, the coil was placed and maintained horizontally with the handle pointing leftward [44]. The Montreal Neurological Institute (MNI) coordinates of the stimulation site for the left SMA were -4.36 ± 2.61 , -5.14 ± 1.88 , 64.43 ± 4.04 mm (x, y, z, mean $\pm$ SD; n = 20) [18] and were consistent with those reported in the literature [40,41,46–48].

To disrupt the SMA activity, continuous theta burst stimulation (cTBS) was delivered at 80% of aMT of FDI (cTBS_{SMA}; n = 10). Repetitive CTBS pulses were delivered in the form of bursts of three pulses at 50 Hz at a rate of 5 Hz (total 600 pulses) [49]. For the SHAM group (cTBS_{SHAM}; n = 10), the same stimulation parameters were used, but the coil was placed perpendicular over the SMA region such that no relevant current flow was induced in the cortical tissue [50–53]. The reduced corticospinal excitability and altered EEG measures lasts about 60 min [49] and 30 min [54,55], respectively.

Experimental Procedures

Each subject participated in two sessions separated by ~14 days. In the first session, participants underwent a structural MRI of the brain, general assessment of the body, and familiarization trials with the force platform. In the second session, we performed EEG, cTBS, and the two balance tasks. Participants were instrumented with EEG, followed by assessment of the resting state EEG activity. Then, the cTBS procedures as detailed above were conducted. After which, the resting state EEG activity was reassessed. All participants performed SRT followed by PT. Following the two balance tasks, resting state EEG was reassessed. All procedures (including post tasks resting state EEG) were completed within 27.2 ($\pm$ 1.4) minutes following cTBS.

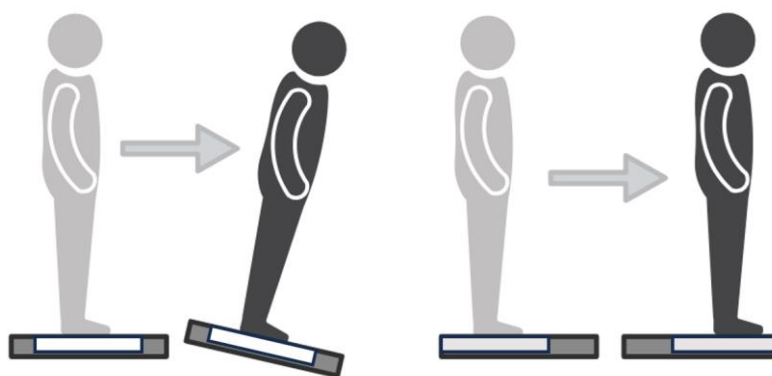


Figure 1. Depiction of each task. (Left) Sway Reference Task, where the platform tilts in reference to the participants' center of pressure. (Right) Perturbation Task, where the participant is translated unexpectedly forward.

Data Analysis

EEG Preprocessing

All 64 channels passed through a zero-phase notch filter (60 Hz) to remove line noise, and a zero-phase bandpass filter (4th order, 0.1 Hz to 100 Hz, Butterworth). The electrooculography (EOG) channels were used in an H-Infinity filter ($q = 1e-11$, $\gamma = 1.15$) to remove eye artifacts while retaining brain signals [56]. The remaining 60 EEG channels were re-referenced to the common average reference. Artifact subspace reconstruction (ASR) was applied [57] with a cutoff parameter of 30 [58]. ASR utilized a clean EEG signal with a sliding window of 500ms to denoise the signal. Twenty second epochs, starting with trial onset, were used for SRT, and 1 second before and 3 seconds after perturbation onset was used to epoch PT. The potential sources of the cleaned EEG signal were determined through independent components analysis (ICA) with principal component analysis (PCA). DIPFIT in EEGLAB was used to fit dipoles to the provided independent components (ICs). ICA assumes the number of ICs to be equivalent to the number of given channels, but some ICs were removed due to their dipoles being outside of EEGLAB's boundary element model (BEM) or ICs that were primarily noise due to channel, muscular, ocular, or bundle artifacts, determined through visual inspection.

EEG Source Localization

A k-means clustering algorithm, with a k value of 5 [18] was applied to the remaining ICs from both SRT and PT tasks within each group based on similarities in calculated features such as dipole 3D location. Only ICs that accounted for at least 85% of variance (less than 15% residual variance) and within 3 standard deviations of the cluster centroid were kept for source localization. The IC that accounted for most of the variance was selected for each participant in each cluster. The Brodmann Areas (BA) for each cluster were determined using the Yale Bioimaging Suite [59] and a deviation of ± 5 mm of the cluster centroids' Talairach coordinates. Clustering was computed using dipoles for cTBS_{SMA} from the SRT, from the PT, and from combined tasks (CT), and repeated for cTBS_{SHAM}. All clusters included independent components from at least 60% of subjects suggesting the clusters were representative of the tasks and most of the participants. Our region of interest was the fronto-central region, of which both groups had one cluster centroid during CT clustering, and these were used for further analysis. These CT clusters had over 80% of subjects contributing during both PT and SRT.

The power spectrum was calculated for each independent component using the pwelch function in MATLAB (MATLAB 2022a, Mathworks, Natick, MA) with non-overlapping Hamming windows with the default frequency resolution of $\pi/256$ rad/sample. Relative power for delta (1–4 Hz), theta (4–8 Hz), alpha (8–12 Hz), beta (12–30 Hz), and low gamma (30–50 Hz) frequency bands were calculated by summing the power over each frequency band and normalized with respect to the total power of the PSD (from 1–50 Hz) for each independent component.

cTBS over SMA and the fronto-central brain response during PT

Because our secondary aim was to investigate the effects of cTBS over SMA on the EEG activity in the fronto-central region, we selected an independent component (IC) over the fronto-central region by examining both the two-dimensional topoplots of all the ICs remaining after EEG data cleaning and the corresponding dipole projections in three-dimensions for each subject [31]. A single IC was chosen in the fronto-central brain region for each subject, based on the latency of a large, consistent event related response for each subject [23]. If the fronto-central response was unclear or distributed between a couple of ICs, of these, the IC which accounted for the largest amount of data variance was selected [23]. The centroid of the 10 equivalent dipoles, one per subject, was determined through a single k-means clustering approach, separately for each group. To understand the effects of cTBS on the fronto-central region, we compared the relative power computed for each subject (individual ICs, as described above) between SMA and sham groups.

Statistical Analyses

We used maximum likelihood linear models because this approach avoids restrictive assumptions of other approaches such as repeated measures ANOVA and accommodates potential missing values. Our clustering step identified EEG sources with different locations across groups, thus we ran separate linear mixed models for each cluster within each group (cTBS_{SMA} and cTBS_{SHAM}) to investigate differences in EEG source power between SRT and PT. Linear mixed models with level 2 within-subject factor Task (SRT, PT), level 5 within-subject factor frequency band (delta, theta, alpha, beta, and low gamma), and interaction between task and frequency bands were included in the model.

Next, we studied the effects of cTBS over SMA on EEG source power over the fronto-central region. For EEG frontocentral source relative power, we ran linear mixed models with level 2 between-subject factor group (cTBS_{SMA}, cTBS_{SHAM}), level 5 within-subject factor frequency band (delta, theta, alpha, beta, and low gamma), with the interaction between group and frequency bands. Post-hoc comparisons were performed using Fisher LSD test with appropriate Bonferroni corrections. All the statistical analyses described thus far in this section were carried out using SPSS software (SPSS version 21, SPSS Inc.; Chicago, IL).

3. Results

3.1. Across-Task Shared EEG Sources

Twenty participants successfully completed the protocol, 10 participants received sham cTBS (cTBS_{SHAM}) and another 10 participants received cTBS (inhibitory) over left SMA (cTBS_{SMA}), before performance of SRT and PT. After preprocessing and artifactual source removal, the equivalent dipoles of the remaining sources were clustered using information from SRT and PT (cTBS_{SHAM}, Figure 2; cTBS_{SMA}, Figure 3), and the participant groups were computed separately. For the cTBS_{SHAM} group, common sources across tasks were found in the Cingulate Gyrus (BA 23 and 24) and the visual cortex (BA 19). In the cTBS_{SMA} group, common sources included the SMA (BA 6) and visual cortex. Because of our interest in the fronto-central region, a cluster in the ventral anterior cingulate (Talairach: [2, 10, 24]) for the cTBS_{SHAM} group and a cluster in the SMA region (Talairach: [-9, 1, 41]) for the cTBS_{SMA} group was selected as clusters of interest for further analysis.

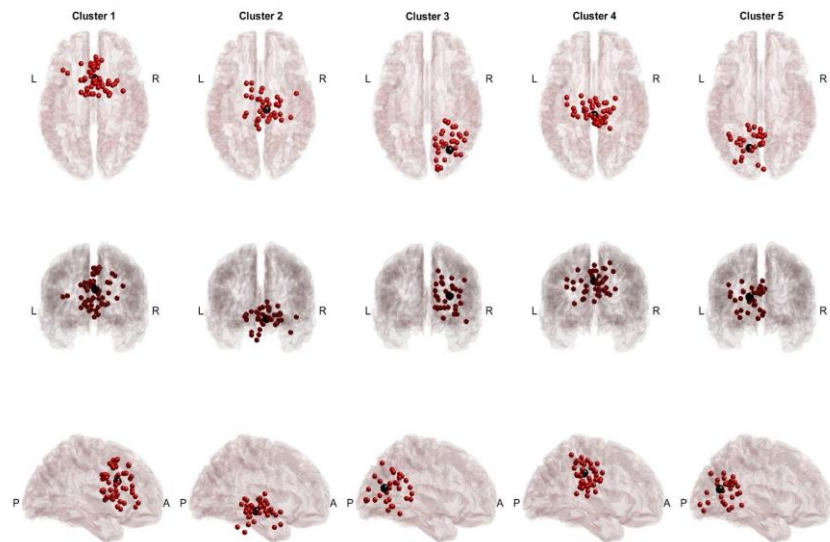


Figure 2. cTBS_{SHAM} Cross-Task Dipoles and Centroids. Red dots represent equivalent dipoles, and black dots represent the cluster centroid. Each cluster is in a column with superior, posterior and lateral views.

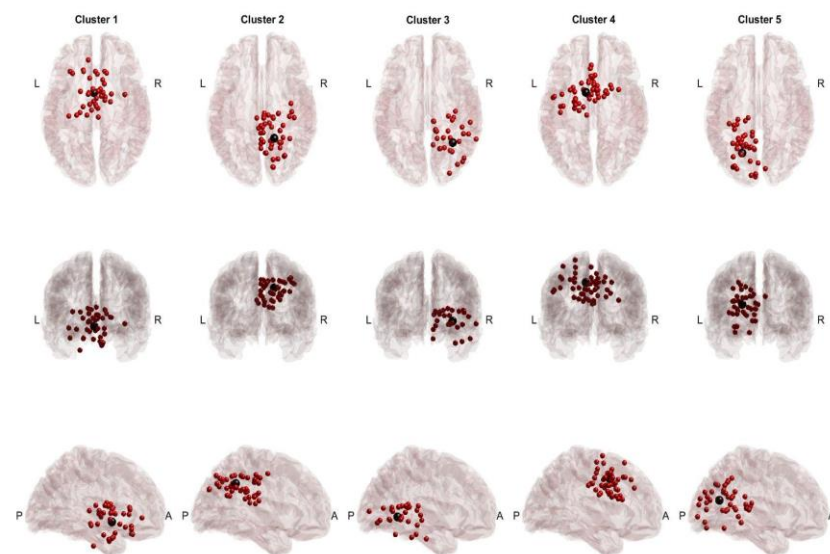


Figure 3. cTBS_{SMA} Cross-Task Dipoles and Centroids. Red dots represent equivalent dipoles, and black dots represent the cluster centroid. Each cluster is in a column with superior, posterior and lateral views.

3.2. Relative Power Comparison within Cross-Task Clusters

We compared relative EEG power at different frequency bands between tasks within each group's fronto-central cluster. For the Ventral Anterior Cingulate (BA 24) in the cTBS_{SHAM} group, we found significant difference in relative EEG power across two tasks (significant Task $\times$ Frequency bands interaction: $F_{4, 94.352} = 21.352$; $p < 0.001$; main effect of Frequency bands: $F_{4, 94.352} = 60.958$; $p < 0.001$). Post hoc comparisons found significantly higher delta band power ($p < 0.000001$) and lower

alpha band power ($p = 0.0098$) during PT when compared SRT. No other comparisons were found to be significant (all p values > 0.05).

Similarly, for the SMA (BA6) region in the cTBS_{SMA} group, we found a significant difference in relative EEG power across two tasks (significant Task $\times$ Frequency bands interaction: $F_{4, 94.352} = 9.537$; $p < 0.001$). Post hoc comparisons found significantly higher delta band power ($p < 0.00022$) and lower alpha band power ($p = 0.00052$) during PT when compared to SRT. No other comparisons were found to be significant (all p values > 0.05).

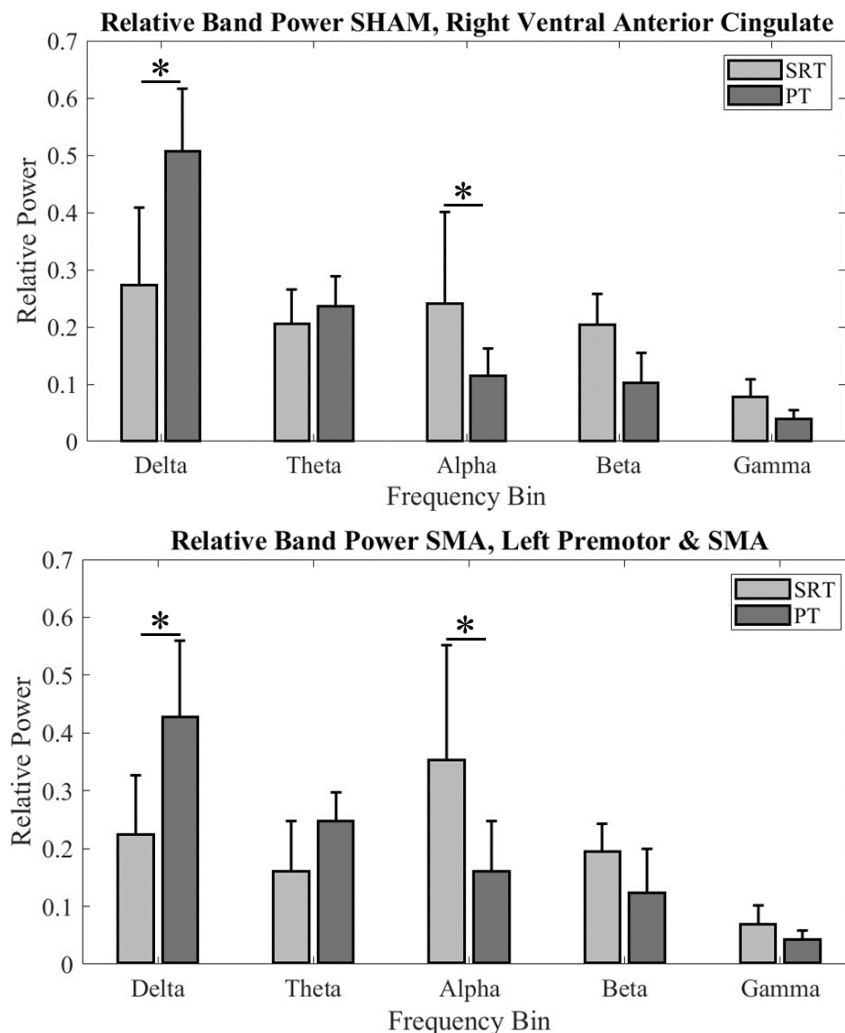


Figure 4. Band relative power across participants for (Top) cTBS_{SHAM} group Cluster 1 and (Bottom) cTBS_{SMA} group Cluster 4. An * denotes statistical significance of $p < 0.05$.

3.3. Fronto-Central Activation during PT Across-Group Localization

Because the secondary aim was to investigate the effects of cTBS over SMA on the EEG activity in the fronto-central region during PT, we focused our analysis on clusters formed using PT-related ICs in this region for each cTBS_{SMA} and cTBS_{SHAM} group. The Talairach coordinates of the cluster centroids in the fronto-central region were (0, 12, 42) for the cTBS_{SHAM} group, which suggests activation within BA 6 (Left SMA), and (2, -2, 48) for the cTBS_{SMA} group, which suggests activation within BA 6 (Right SMA). Band relative powers were computed for each IC from a participant contributing to these clusters and compared across groups (Figure 5). We found a significant difference in frequency band power across the two groups (significant Group $\times$ Frequency bands interaction: $F_{4, 195.187} = 3.932$; $p = 0.004$; main effect of Frequency bands: $F_{4, 195.187} = 114.41$; $p < 0.001$). Post hoc comparison found a significantly lower delta frequency band power following cTBS over SMA (cTBS_{SMA}) when compared with the cTBS_{SHAM} group ($p = 0.038$). No other comparisons were found to be significant (all p values > 0.05).

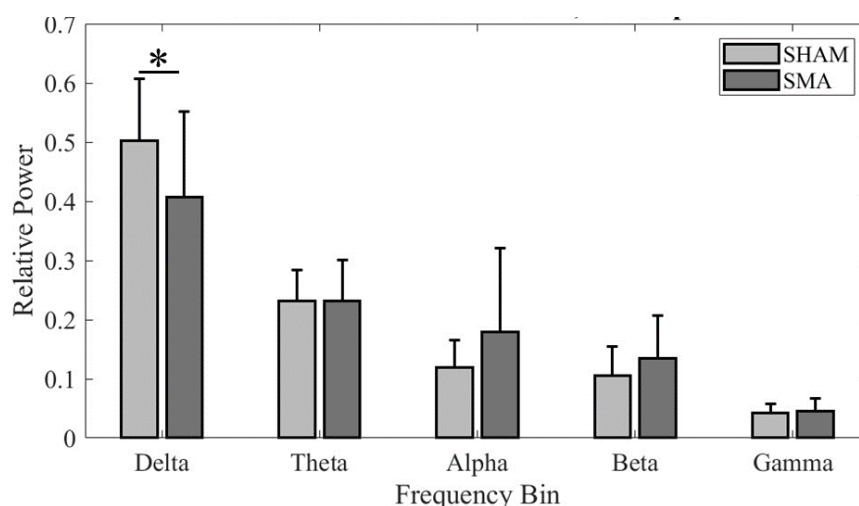


Figure 5. PT band relative power across groups for fronto-central cluster dipoles. An * denotes statistical significance of $p < 0.05$.

4. Discussion

In this study, we compared the relative power of cortical sources identified using EEG between two commonly studied challenging balance tasks, SRT and PT in neurotypical adults. We also investigated whether cTBS over SMA can alter the EEG activations during PT in neurotypical adults. The novel findings from this study are: (1) For the ventral anterior cingulate region in the cTBS_{SHAM} group, we found higher delta band relative power and lower alpha band relative power during PT when compared to SRT. (2) Similar differences were observed in delta and alpha band relative power between PT and SRT for the SMA region in the cTBS_{SMA} group. (3) For the perturbation task, cTBS (inhibitory) over SMA significantly reduced the delta band relative EEG power over the frontoparietal region when compared with sham stimulation.

In our study, two groups of individuals performed both the perturbation task and the sway reference task. We identified EEG sources of activations and found commonalities and differences in the location of EEG clusters between the two groups. Mainly, we found EEG clusters localized within the frontocentral regions (cingulate gyrus, SMA), posterior cingulate cortex (PCC; BA 23 and 31), and visual cortex (VC; BA 17, 18 and 19), a finding consistent with previous studies [16–18,21,60]. However, the locations of these clusters identified in two groups were distinct. For example, in the cTBS_{SHAM} and cTBS_{SMA} groups, our analysis found a cluster in the frontocentral regions but these clusters were localized within ventral anterior cingulate and supplementary motor area, respectively. As the purpose of this study was to compare EEG activations between two tasks, we performed within-group analysis for each cluster.

Lower Alpha Band Relative Power during PT When Compared to SRT

We found a significant decrease in alpha frequency band in the fronto-central region for PT as compared to SRT in both groups. Lower alpha frequency spectral power during a standing balance task has been argued to reflect higher task difficulty, i.e., more challenging balance task [10,14,18,61,62]. For example, Kahya et al. (2022) increased difficulty and diverted attention through a standing balance task with mental arithmetic and found a decrease in alpha-band power as compared to quiet standing [62]. Lower alpha power during performance of PT than SRT might be related to increased information processing necessary to process and/or respond to the platform translation resulting from reduced inhibition by higher centers [10,61,63,64].

Higher Delta Band Relative Power during PT When Compared to SRT

We found a significant increase in delta frequency band relative power during PT as compared to SRT in the frontocentral region for both groups. Delta oscillations have been shown to be involved

in cognitive processes such as decision-making and attentional processes [65] and are known to impact behavioral outcomes [66], where the difficulty of a postural task has been associated with increased delta band activity [67]. Slower brain oscillations due to their longer temporal window of processing information suggest involvement of neurons in widespread brain areas [68,69]. Primate work has shown interactions between parietal sensory areas and motor areas in the frontal region in the delta frequency range during a somatosensory discrimination task [68]. The presence of delta band power in the fronto-central brain region during both balance tasks might represent long-range integrative processes with greater engagement of cognitive resources [70] during PT (i.e., greater delta band power) than SRT. Therefore, it is conceivable that greater task demand and challenge to the standing balance led to significantly higher delta band power for PT than SRT.

Relation between Brain Oscillations and the Cortical Potentials Following Balance Perturbations

The superimposition of oscillations in lower frequency bands such as delta, theta and alpha frequency bands may partly underlie the generation of cortical event-related potentials following balance perturbations [71–75]. Imposed mechanical perturbations such as the one delivered in PT are associated with characteristic event-related potentials (ERPs) in the EEG activity. Mainly, a positive potential (P1) is generated over the parietal-central region within the first 50–70 ms after the onset of perturbation. This response is followed by a large negative potential (N1) generated over the fronto-central region with a peak latency of 100–200 ms after the onset of perturbation [21,31,76,77]. This N1 response has been suggested to indicate the involvement of higher-order processing in the form of error detection (i.e., difference between the actual balance state due to balance perturbation and the anticipated balance state) and signaling postural responses to the destabilizing effects of balance perturbations [12,31,77]. The size of N1 potential is small during SRT where sensory feedback regarding motor outputs during ongoing balance control is altered such that the effects are a function of the action of the participant [33]. Although the presence of a P1 response during SRT is debatable, our earlier work has shown involvement of bilateral posterior parietal cortices during SRT [18]. The N1 response is followed by late evoked responses, the P2 and the N2 responses. There is a debate on the role of these late responses with some studies suggesting their involvement in cortical sensorimotor processing while others linked them with a shift in attention to novel perturbation events [30,78,79]. In addition, the delta band power is known to increase while the alpha band power decreases in response to stimulus and task demands [80,81]. We suggest that larger relative delta band power (and smaller relative alpha power) for PT when compared with SRT might explain larger and clearly patterned ERPs observed following platform translation perturbations [80,81].

cTBS over SMA Altered Delta Band Power over the Fronto-Central Region during the PT Task

A cortical response in the fronto-parietal region is a well-documented phenomenon following mechanical perturbations of the standing platform (viz. translation). Clustering of fronto-central independent components for each participant showed activations of the SMA region (BA 6) for both groups. The study was designed to consider all trials together for clustering to provide better understanding of the changes on cortical activity measured as EEG power in five frequency bands following inhibitory cTBS protocol. We found a significant decrease in the delta frequency relative band power within the SMA region following cTBS over SMA when compared to sham stimulation. Previously, EEG frequency analysis of participants at rest reported significant decreased power in the delta band following cTBS [82,83]. Our results support this and report its occurrence during a standing balance task. cTBS might have increased neural noise in the stimulated area, thus disrupting the synchronicity of neural activities [84–86]. The reduction in delta frequency band relative power within the SMA following cTBS might thus suggest disruption in long-range integrative processes between frontal and parietal regions necessary for the performance of PT [16–24]. The spread of TMS stimuli to distant regions through cortico-cortical connections is well known [87,88]. The fronto-parietal regions are known to have long-range cortico-cortical connections with Broadman area 4, premotor areas, cingulate areas, and parietal cortices [89,90]. Also, smaller amplitude of delta oscillations following cTBS might have influenced the generation of ERPs in the fronto-central region

affecting the functional postural response following platform translation. However, this remains to be known. Our study included only three trials per perturbation condition thus limiting the statistical power to investigate the effects of cTBS over SMA on the amplitude and latency of ERPs and behavioral implications [91]. Our study raises the possibility of using cTBS to alter ERP-components by interfering with the underlying oscillations.

Our previous work using the sway reference task [18], found changes in EEG band power within bilateral parietal cortices and cingulate gyrus following cTBS over SMA, a fronto-central region, when compared with sham stimulation. Although this earlier study did not study the effects of cTBS on delta band power, it found modulation in theta frequency band power across different levels of task difficulty following cTBS than sham stimulation. It also found a decrease in alpha band power following cTBS when compared to sham stimulation during the sway referencing task, a finding not observed in the current study that used a perturbation task to challenge the balance. The lack of an alpha effect in this study might be due to already lower alpha band power during PT (see Figure 4), and the inability of cTBS to lower it further, i.e., a floor effect.

5. Conclusions

Our findings suggest PT is a more challenging balance task when compared with SRT requiring greater cognitive function and attentional control as indicated by higher delta and lower alpha relative frequency power. Thus, the results of our study could be relevant to researchers and clinicians to select between SRT and PT, depending on the individual's need. Furthermore, a training paradigm targeting the respective mechanisms should account for the differences in expected cortical activations. cTBS modulated delta power in the fronto-central cortical regions during PT. Additional research is needed to determine how such an interference with delta oscillations affects the ERPs following platform perturbations. By isolating circuits that exhibit a favorable response to cTBS intervention, we will advance understanding of precise brain circuits associated with balance control. Mechanistic findings may lead to cortical targets for effective neuromodulation strategies for rehabilitation of balance control in clinical populations.

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