Spectral analysis of body movement during deep brain stimulation in Parkinson's disease

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Abstract

Background: The characteristics of Parkinson's disease (PD) include postural instability and resting tremor. However, reductions of tremor amplitude do not always improve postural stability.

Research Question: What is the effect of deep brain stimulation (DBS) of the subthalamic nucleus (STN) on spectral analysis of body movement in patients with PD when tested without anti-PD medication? The effect of visual cues was also studied.

Methods: Ten patients with PD (mean age 64.3 years, range 59-69 years) and 17 control participants (mean age 71.2 years, range 65 -79 years) were recruited. Spectral power following a period of quiet stance (35s) was analysed in three different spectral power bands (0-4Hz, 4-7Hz and 7-25Hz). Motion markers were secured to the head, shoulder, hip, and knee, which recorded movements in two directions, the anteroposterior and lateral.

Results: DBS STN significantly changed the spectral distribution pattern across the body in the anteroposterior ($p=0.029$) and lateral directions ($p\leq0.003$). DBS predominantly reduced spectral power at the head ($p\leq0.037$) and shoulder ($p\leq0.031$) in the lateral direction. The spectral power of the lower and upper body in patients with PD with DBS ON were more similar to the control group, than with DBS OFF. Visual cues mainly reduced spectral power in the anteroposterior direction at the shoulder ($p\leq0.041$) in controls and in patients with PD with DBS ON.

Significance: There is an altered postural strategy in patients with PD with DBS ON as shown by an altered spectral power distribution pattern across body segments and a reduction of spectral power in the lateral direction at the head and shoulder. A reduction of spectral power in controls and in patients with PD with DBS ON suggests that visual cues are able to reduce spectral power to some extent, but not with DBS OFF where postural sway and power are larger.

Keywords: Parkinson disease; Spectral analysis; fast-Fourier Transformation; Body movement; Deep brain stimulation

Introduction

Tremor is approximately sinusoidal and has a relatively fixed frequency across the body [1], though its amplitude and shape can vary [2, 3]. For example, spectral analysis of movement in patients with Parkinson's resting tremor has shown it to have a frequency of between 4 to 7Hz that varies in amplitude between individuals [4]. Tremor in Parkinson's disease (PD) is believed to be the result of degeneration of the nigro-striatal pathway and depletion of dopamine in the substantia nigra pars compacta [4]. However, the origins of tremor frequency and amplitude variations are unknown. Thus, any tremor-generating signal and its treatment are likely to affect different parts of a complex subcortical network. Little consideration has been given to frequency and amplitude variations in Parkinsonian resting tremor during stance [2] where a suitable measure is the total power content across a broad spectrum [5, 6].

In addition to tremor, axial motor features of PD include postural instability and gait impairments. These symptoms are debilitating and do not always respond to dopamine replacement therapy [7]. Deep brain stimulation (DBS) of the subthalamic nucleus (STN) is an established treatment for tremor but its effects on postural instability are less clear with some studies indicating no improvement [7-10]. In fact, in randomised-controlled trials more falls were reported by patients with DBS STN compared to other treatments [11, 12] and, in a double-blind study, St George and colleagues showed that balance was not significantly different between DBS STN (n=14) and the best medically treated state prior to DBS surgery [13]. Further studies are therefore

necessary to elucidate and quantify the effects of DBS STN on postural dynamics and body movement.

Our aim was to quantify the effects of DBS STN in PD on spectral power (using fast-Fourier Transformation), during quiet stance, at points of articulation along the length of the body (thus measuring the movement at segmental levels). Our hypothesis was that DBS STN would reduce spectral power similarly across body segments in the anteroposterior and lateral directions but vision would have no effect. The novelty of this study is the approach of studying the power spectra, objectively, at different frequency ranges and different proximal segmental levels of the body. This contrasts traditional observer-rated assessments such as the Unified Parkinson's Disease Rating Scale (UPDRS). As stated by Fasano and colleagues [7] "such subjective rating scales provide crude estimates of potential changes and can easily miss the specific effects on selected balance responses".

Methods

Ethical approval

The experiments were conducted in accordance to the Declaration of Helsinki and all participants provided signed, informed, consent. The study was approved by the Regional Ethical Review Board (411/2006), Lund, Sweden.

Participants

Twenty-five patients were eligible (22 males and 3 females) meeting entry criteria of idiopathic PD responsive to L-Dopa, between 50-70 years, with at least one years' use of bilateral DBS STN. Fifteen patients were excluded due to concomitant diseases (e.g. loss of peripheral sensation in the lower extremities, severe comorbidity/pain), an inability to cooperate or an inability to stand for two minutes without support. Ten individuals with PD participated (9 males and 1 female, mean age 63.8 years (SD 4.1 years, range 59-69 years). DBS settings and the neurosurgical procedure are described in Table 1 and elsewhere [8]. All patients were recruited from the Department of Neurosurgery, Skåne University Hospital. A control group comprised 17 healthy adult participants (9 males, mean age 71.2 years (SD 4.1 years, range 65 -79 years)) with no history of falls or neurological/musculoskeletal conditions.

Procedure

Participants stood upright in quiet stance with eyes open or eyes closed. In participants with PD, all anti-PD medications were withdrawn overnight before testing (from 10pm) and all were kept as in-patients. The following morning an independent healthcare professional programmed the DBS to deliver stimulation (ON) or turn the device off (OFF). The orders of DBS ON/OFF and eyes closed/eyes open tests were randomised by placing test order codes in unmarked envelopes to avoid systematic differences and bias. The DBS settings were concealed to personnel handling the tests. The test session was repeated in the other DBS state using the same eyes open /eyes closed order. Tests started a minimum of 30 minutes after programming the DBS (i.e., OFF or ON). A counter-balanced test order design was used to minimise any systematic effects from

ON/OFF changes. In controls, test order (eyes open /eyes closed) was randomised using a Latin square design.

Experimental design

A 35-second period of quiet stance was recorded. Each participant was instructed to stand in an erect and relaxed posture, barefoot, with arms folded across the chest. The participant's heels were 3cm apart and feet at an angle of approximately 30º open to the front using guidelines. The participant stood 1.5m away from a wall and instructed to focus on a 4 x 6cm image directly ahead at eye level or stand with their eyes closed. They listened to calm classical music through headphones during tests to reduce movement references from external noise sources. A five-minute rest period was given to participants between eyes open and eyes closed tests. Participants with PD had a 30-minute break between tests in which the DBS was reprogrammed.

An ultrasound 3D motion capture system (Zebris™ CMS-HS Measuring System) measured movement at 50Hz at five anatomical proximal bony landmarks on the right side of the patient, which faced the motion detector unit. The first marker (Head) was attached to the patient's cheekbone (os zygomaticum), the second marker (Shoulder) to the shoulder (tuberculum majus), the third (Hip) to the hip bone (crista iliaca), the fourth (Knee) to the knee (lateral epicondyle of femur), and the fifth marker (Ankle) to the anklebone (lateral distal fibula head). Data from the ankle marker served as a tool to visualise whole-body postural sway only. The markers, fixed to the selected recording sites with adhesive tape, remained attached to the patients until all assessments were completed. Each marker registered its position in three directions, i.e., anteroposterior, lateral and vertical. The measurement resolution in all directions was 0.4 millimetres. The fast-Fourier transformation (FFT) analysis was performed on raw data normalised

with the patient's height, with the unit and scale including normalisation of [m 10^{-3} m^{-1}] using a customised software, Postcon.

Movement data were converted into 300 FFT samples reflecting the spectral power in the frequency range from 0.08-25Hz. The spectral power was calculated through a Hamming signal filter window and an averaging procedure using Root Mean Square (RMS). The robustness of the analysis was enhanced as the final spectral power spectrum was calculated as the average value from 10 repeated spectral power analyses on raw data shifted one sample before each repeated FFT calculation. The average power spectrum for the 10 repeated FFT calculations was calculated using linear weighting. In this study, the average spectral power was calculated for three frequency bands: 0-4Hz, 4-7Hz and 7-25Hz. These bands were selected as the 4-7Hz band is mainly affected by PD resting tremor [4] and the 7-25Hz band by postural 'action' tremor which can contain sidebands associated with tremor resonance [5]. The 0-4Hz lower frequency band corresponds to slower alterations of movement and is unrelated to tremor amplitude in patients with PD [14]. We measured spectral power with eyes open and eyes closed under quiet stance at different levels of the body and assessed the effect of DBS STN. By studying the spectral power in bands, we were able to estimate the underlying postural dynamics.

Statistical Analysis

Log-transformed mean spectral power values in the anteroposterior and lateral directions and in three spectral bandwidths (0-4Hz; 4-7Hz and 7-25Hz), were analysed with repeated measures general linear model (GLM) Analysis Of Variance (ANOVA). The GLM ANOVA method was used after ensuring that all dataset combinations produced model residuals that had normal or close to normal distribution, thus ensuring

its validity [15]. The main factor combinations analysed for their effects on power spectra were:

1) Group (Controls vs PD with DBS OFF, 1 degree of freedom (df)) and Vision (eyes open vs. eyes closed, 1 df); where the model parameter Group is a Between-Subjects factor, and the model parameter Vision is a Within-Subjects variable.

2) Group (Controls vs PD with DBS ON, 1 df) and Vision (eyes open vs. eyes closed, 1 df); where the model parameter Group is a Between-Subjects factor and the model parameter Vision is a Within-Subjects variable.

3) DBS (PD with DBS ON vs PD with DBS OFF, 1 df) and Vision (eyes open vs. eyes closed, 1 df); where the model parameters DBS and Vision are Within-Subjects variables.

Furthermore, the spectral power distribution pattern across segments was analysed between groups and DBS state using the GLM ANOVA with main factors: Vision (eyes open vs. eyes closed, 1 df); and Segment ([Head Shoulder Hip Knee], 3 df), where the model parameters Vision and Segment are Within-Subjects variables.

The main rationale for a separate analysis of movement activity in the anteroposterior and lateral directions is the directional difference in the biomechanical design of the body. In a lateral direction, the movement pattern is affected by various musculoskeletal adaptations of the pelvis, knee and lower limb mechanics. In the anteroposterior direction, the biomechanical design does not inherently provide stability and needs to be maintained by continuous muscle activity.

For post-hoc analysis, we carried out within-subjects paired comparisons to study the effects of DBS and Vision with Wilcoxon matched-pairs signed-rank test (Exact sig. 2-tailed). Between-groups comparisons (controls vs PD with DBS ON and controls vs PD with DBS OFF) were performed with Mann-Whitney U Tests (Exact sig. 2 tailed)

[15]. For completeness, a full factorial post hoc analysis was performed for Vision (eyes open vs. eyes closed) and between groups and between DBS states. Non-parametric statistics were used as not all datasets were normally distributed before or after logarithmic transformation. In the statistical analyses, p-values<0.05 were considered significant in the GLM ANOVA, whereas in the post-hoc statistics a Bonferroni corrected level of p<0.025 was applied. The statistical analyses were performed with SPSS version 26 [16].

Results

Anteroposterior Power

Controls vs DBS OFF

In the ANOVA, the main factor Group was significant, see Table 2. There were higher levels of power in patients with PD with DBS OFF compared to controls at the knee (p=0.026). There were also higher levels of power with eyes closed compared with eyes open at the hip (p=0.024). In the ANOVA, the interaction Group x Vision revealed no significant effects.

Post-hoc tests showed that the knee power was significantly larger in PD with DBS OFF compared to controls in the 7-25Hz band with eyes closed (p=0.008), see Figure 1.

Controls vs DBS ON

In the ANOVA, the main factor Group was significant, see Table 2. There were lower levels of power in patients with PD with DBS ON compared to controls at the shoulder in the 7-25Hz band (p=0.024) and at the hip in the 4-7Hz band (p=0.020). In the ANOVA, Vision reduced power at the shoulder in the 0-4Hz band (p=0.041), the 4-7Hz band (p=0.027) and 7-25Hz band (p=0.023) and at the hip in the 0-4Hz band (p=0.009). The main factor interaction Group x Vision revealed no significant effects.

Post-hoc tests showed a reduced power in patients with PD with DBS ON compared with controls with eyes open at the shoulder in the 4-7Hz band ($p<0.001$) and in the 7-25Hz band ($p=0.014$), see Figure 1.

DBS OFF vs. DBS ON

In the ANOVA, the main factor DBS was significant, see Table 2. There were higher levels of power in patients with PD with DBS OFF compared to DBS ON at the shoulder in the 4-7Hz band ($p=0.034$). In the ANOVA, Vision and the interaction DBS x Vision revealed no significant effects.

Post-hoc tests showed a larger power in PD with DBS OFF compared with PD with DBS ON with eyes closed at the hip in the 4-7Hz band ($p=0.023$), see Figure 1.

Lateral Power

Controls vs DBS OFF

In the ANOVA, the main factor Group was significant, see Table 3. There were higher levels of power in patients with PD with DBS OFF compared to controls at head in the 4-7Hz band ($p=0.006$) and 7-25Hz band ($p<0.001$). In the ANOVA, Vision and the interaction Group x Vision revealed no significant effects.

Post-hoc tests showed that power was significantly higher in patients with PD with DBS OFF at the head in the 7-25Hz band with eyes closed ($p=0.001$) and in the 4-7Hz ($p=0.004$) and 7-25Hz ($p<0.001$) bands with eyes open, see Figure 2.

Controls vs DBS ON

In the ANOVA, the main factor Group was significant, see Table 3. There were higher levels of power in patients with PD with DBS ON compared to controls at the head in the 7-25Hz band ($p<0.001$). We also found lower levels of power in patients with PD with DBS ON at the hip in the 4-7Hz band ($p=0.002$) and 7-25Hz band ($p<0.001$). In the ANOVA, Vision reduced power at the head in the 0-4Hz band ($p=0.047$). In the ANOVA, the interaction Group x Vision revealed no significant effects.

Post-hoc tests showed that the power was significantly higher in PD with DBS ON at the head in the 7-25Hz band, which applied for both eyes closed and open ($p<0.001$), see Figure 2. Power was significantly lower in PD with DBS ON at the hip in the 4-7Hz band with eyes open ($p=0.016$). Power was also significantly lower in PD with DBS ON at the hip in the 7-25Hz band, which applied for both eyes closed and open ($p<0.001$). Power was significantly lower in PD with DBS ON at the knee in the 4-7Hz band with eyes open ($p=0.023$).

DBS OFF vs. DBS ON

In the ANOVA, the main factor DBS was significant, see Table 3. There were higher levels of power in patients with PD with DBS OFF compared to DBS ON at the head in the 0-4Hz ($p=0.025$) and 4-7Hz ($p=0.037$). There were also higher levels of power in patients with PD with DBS OFF at the shoulder in the 4-7Hz band ($p=0.031$) and 7-25Hz band ($p=0.028$). In the ANOVA, Vision and the interaction DBS x Vision revealed no significant effects.

Post-hoc tests showed that the power was significantly higher in PD with DBS OFF than DBS ON at the head in the 0-4Hz band with eyes closed ($p=0.020$) and in the 4-7Hz band with eyes open ($p=0.014$), see Figure 2. Power was also significantly higher

in PD with DBS OFF than ON at the shoulder in the 0-4Hz band with eyes closed (p=0.008) and in the 7-25Hz band with eyes open (p=0.014). Power was significantly higher in PD with DBS OFF than ON at the in the 4-7Hz band with eyes open (p=0.020). Power was significantly lower in PD with DBS ON at the knee in the 0-4Hz band with eyes closed (p=0.023).

Eyes open vs. Eyes closed

Paired statistics (Wilcoxon) were used for the post-hoc examination of Vision. Both for the spectral power in anteroposterior and lateral directions, vision had no significant effect, reaching Bonferroni corrected level, within any spectral band or segmental level for any group or DBS state.

Segmental spectral power distribution

In controls, the spectral power distribution systematically decreased in anteroposterior direction from the upper segments to the lower segments in the 0-4Hz band ($p<0.001$), see Table 4 and Figure 3. However, in the 4-7 Hz band (p=0.001) and 7-25 Hz band (p=0.004) the spectral power systematically decreased from the lower to the upper segments. Similarly, in patients with PD with DBS ON, the spectral power distribution systematically decreased from the upper segments to the lower segments in the 0-4Hz band (p=0.001). Moreover, in the 4-7 Hz band (p=0.029) and 7-25 Hz band ($p<0.001$) the spectral power systematically decreased from lower to the upper segments. However, in patients with PD with DBS OFF the spectral power distribution pattern was weaker. The spectral power systematically decreased from the upper segments to the lower segments in the 0-4Hz band (p=0.034). Furthermore, the spectral power systematically decreased from lower to the upper segments in the 7-25 Hz band only (p=0.017).

In controls, the spectral power distribution systematically decreased in the lateral direction from the upper segments to the lower segments in the 0-4Hz band ($p=0.003$). However, in the 4-7 Hz band ($p=0.036$) and 7-25 Hz band ($p=0.017$) the spectral power systematically decreased from the lower to the upper segments. Similarly, in patients with PD with DBS ON the spectral power distribution systematically decreased from the upper segments to the lower segments in the 0-4Hz band ($p=0.025$). Moreover, in the 4-7 Hz band ($p=0.003$) and 7-25 Hz band ($p<0.001$) the spectral power systematically decreased from the lower to the upper segments. However, in patients with PD with DBS OFF the spectral power distribution pattern was weaker. The spectral power systematically decreased from the upper segments to the lower segments in the 0-4Hz band ($p=0.043$).

Discussion

A significantly altered spectral power distribution across body segments and a reduction of spectral power in the lateral direction at the head and shoulders indicated an altered postural strategy with DBS ON. A decrease in tremor is a well-known effect of DBS STN and is consistent with the findings of reduced spectral power >4Hz [2, 17-20]. In a review, Gross and Lozano [21] noted a 45–97% decrease in tremor amplitude from DBS, levels also confirmed by a more recent study [2]. DBS appears to reset the primary oscillator and establishes control over different parts of a complex and possibly widely distributed mechanism. It may be because the control network and the area affected by the pathological lesion is so widely distributed that DBS has such variable results [2]. Another explanation is the degree of tremor dominance. A person with high tremor dominance (called postural instability gait disorder) would respond better to DBS.

The 0-4Hz band was not altered by DBS STN except at the head in the lateral direction as shown in the ANOVA. This finding is consistent with Matsuda and colleagues who found little difference between patients with PD and controls on ground reaction forces of low frequency [22]. The low frequencies of movement are perhaps attributed to alterations of body posture. However, only a few studies, that are mostly case studies, have addressed the effect of DBS on posture in PD [7]. Still, from one larger study, there was a suggestion that posture is less consistently altered by DBS STN compared to other sites of invasive stimulation [23].

We also found that DBS STN resulted in a general reduction of power >4Hz at the head and shoulder, but not at the hip and knee, and mostly in the lateral direction. A similar finding to ours was from Powell and colleagues who found that DBS increased the variability of knee and hip movement [24]. Given the proximity of the knee to the foot-floor surface, this finding may partly explain why studies have reported no effect of DBS STN on postural instability [10, 25] or a worsening [9] in force platform recordings. As the knee and hip play a crucial role in flexibility and adaptability in gait [24], it seems plausible that the maintenance of power >4Hz is required for adjusting the postural strategy in the event of postural instability, similar to the strategic changes of posture to balance perturbations in older adults [26]. In line with this notion, we found significantly higher power at lower segments in controls and in PD in DBS ON at frequencies > 4Hz both in anteroposterior and lateral direction, but this movement pattern was weaker or absent in PD with DBS OFF, see Figure 3. Another possibility is that adaptation to the DBS produced an internal re-setting that was disrupted when the DBS is turned OFF resulting in a rebound effect [27] and increased power spectra at lower body levels. Further work is required to evaluate the perseverance of

movement at the knee and hips across the power spectra with DBS STN. Specifically, whether knee and hip movements are adaptive or evidence of impairment.

Another important finding was that power spectra >7Hz at the knee were larger with DBS OFF compared to controls in the anteroposterior direction. However, in the lateral power spectra, head, shoulder and hip spectra >4Hz were larger with DBS OFF compared to controls. The clinical implication of this finding is that observations of tremor or postural instability may be affected by the observer's viewpoint. These directional effects are concordant with Horak and colleagues [28], who found that lateral postural stability was reduced in patients with PD through a loss of trunk flexibility whereas backwards postural stability was reduced by a loss of knee flexion. It is worth noting that trunk and knee flexion are associated with body posture and not linear movement as measured in the current study. Interestingly, and relevant to this finding, another study suggested that the tendency to fall backwards increased after DBS [29]. Vision had a limited effect on spectral power. The effects were mainly at the shoulder in the anteroposterior direction in controls and patients with PD with DBS ON. These effects suggest that visual cues are able to reduce spectral power but not with DBS OFF where postural sway and power are larger. This finding may imply that the visual stabilisation of posture is altered with DBS OFF which is perhaps surprising given that proprioceptive afferents, both joint position sense [30] and passive motion detection [31] are disrupted in PD. Further perturbation-based studies that increase the importance of visual cues are required to explore this.

Study Limitations

The control group was on average 7 years older, which could potentially mean that an age-matched group of patients with PD experience greater deficits than recorded here. However, the segmental power distribution pattern (Figure 3) showed that

controls produce a movement pattern that differs from patients with PD with DBS OFF in the different frequency ranges, but not DBS ON. Another key finding was that the lateral movement pattern and spectral power were mostly affected during DBS OFF.

The degenerative properties of PD means that the effectiveness of DBS may decline over time. In the PD group, the median duration of DBS use was 37 months (range 15-70 months). This length of chronic DBS use would mitigate any changes associated with an acute effect of stimulation. However, the length of use is insufficient to produce habituation [27]. We believe that a median duration of 37 months DBS use provides a stable response, without the suppression or distortion that can develop.

Conclusion

When tested without anti-PD medication, a significantly altered spectral power distribution pattern across body segments and a reduction of spectral power in the lateral direction at the head and shoulder indicates an altered postural strategy with DBS ON. A reduction of spectral power in controls and in patients with PD with DBS ON suggests that visual cues are able to reduce spectral power to some extent, but not with DBS OFF where postural sway and power are larger. Hence, the utility of spectral analysis for whole body motion analysis in PD might extend to therapeutic analysis and the contribution of knee and hip movement.

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Tables

Table 1. Patient characteristics

Patients' characteristics		**Median (range)**
Gender		9 men, 1 woman
Age (years)		65 (59-69)
Duration of disease (years)		18 (10-22)
Treatments		
L-dopa equivalent dose (mg/day) *		416 (294-989)
Duration of DBS treatment (months)		37 (15-70)
UPDRS Scores **		
Scoring of tremor (Item 20 &21)	DBS OFF	2.3 (0.0-12.0)
	DBS ON	0.0 (0.0 – 0.0)
Total Score	DBS OFF	41.0 (35.0-83.5)
	DBS ON	21.5 (11.0-30.5)

* Levodopa equivalent doses calculated according to Østergaard et al. [32], and Calne [33].

** UPDRS part III: Unified Parkinson's disease Rating Scale, motor examination. The maximum total score on the UPDRS part III is 108 points, and higher scores reflect more severe motor symptoms.

Item 20 of UPDRS part III assesses rest tremor in A) the face, lips and chin (scored 0-4), B) hands (right and left, each scored from 0-4), and C) feet (right and left, each scored from 0-4). Item 21 assesses action or postural tremor in the hands (right and left, each scored from 0-4).

The UPDRS assessments were done at the same occasion as the other assessments included in the study.

Table 2. GLM ANOVA analysis of anteroposterior spectral power

Anteroposterior spectral power	Group	Vision	Group x Vision	Group	Vision	Group x Vision	DBS	Vision	DBS x Vision
Position	**Control vs. DBS OFF ***			**Control vs. DBS ON ***			**DBS OFF vs DBS ON ****		
Head									
0 - 4 Hz	0.410 [0.7]	0.330 [1.0]	0.582 [0.3]	0.971 [0.0]	**0.061 [3.8]**	0.817 [0.1]	0.428 [0.7]	0.461 [0.6]	0.378 [0.9]
4 - 7 Hz	0.394 [0.8]	0.494 [0.5]	0.934 [0.0]	0.145 [2.3]	0.274 [1.3]	0.855 [0.0]	0.145 [2.6]	0.399 [0.8]	0.927 [0.0]
7 - 25 Hz	0.140 [2.3]	0.595 [0.3]	0.815 [0.1]	0.199 [1.7]	0.514 [0.4]	0.751 [0.1]	0.971 [0.0]	0.612 [0.3]	0.785 [0.1]
Shoulder									
0 - 4 Hz	0.283 [1.2]	0.243 [1.4]	0.525 [0.4]	0.831 [0.0]	**0.041 [4.6]**	0.902 [0.0]	0.401 [0.8]	0.415 [0.7]	0.412 [0.7]
4 - 7 Hz	0.131 [2.4]	0.615 [0.3]	0.447 [0.6]	**0.094 [3.0]**	**0.027 [5.6]**	0.428 [0.6]	**0.034 [6.5]**	0.330 [1.1]	0.653 [0.2]
7 - 25 Hz	0.646 [0.2]	0.140 [2.3]	0.891 [0.0]	**0.024 [5.7]**	**0.023 [5.9]**	0.501 [0.5]	0.173 [2.2]	0.195 [2.0]	0.666 [0.2]
Hip									
0 - 4 Hz	0.749 [0.1]	0.238 [1.5]	0.244 [1.4]	0.968 [0.0]	**0.009 [7.9]**	0.884 [0.0]	0.550 [0.4]	0.514 [0.5]	0.298 [1.3]
4 - 7 Hz	0.394 [0.8]	**0.024 [5.9]**	0.992 [0.0]	**0.020 [6.2]**	0.160 [2.1]	0.843 [0.0]	0.136 [2.8]	0.796 [0.1]	0.168 [2.4]
7 - 25 Hz	**0.052 [4.2]**	0.777 [0.1]	0.136 [2.4]	0.927 [0.0]	0.115 [2.7]	0.440 [0.6]	0.192 [2.1]	0.848 [0.0]	0.210 [1.9]
Knee									
0 - 4 Hz	0.187 [1.9]	0.188 [1.8]	0.526 [0.4]	0.650 [0.2]	0.482 [0.5]	0.909 [0.0]	0.439 [0.7]	0.291 [1.3]	0.859 [0.0]
4 - 7 Hz	0.465 [0.6]	0.458 [0.6]	0.528 [0.4]	0.442 [0.6]	0.678 [0.2]	0.749 [0.1]	0.327 [1.1]	0.654 [0.2]	0.481 [0.6]
7 - 25 Hz	**0.026 [5.7]**	0.479 [0.5]	0.578 [0.3]	0.215 [1.6]	0.912 [0.0]	0.793 [0.1]	0.242 [1.6]	0.673 [0.2]	0.364 [0.9]

* Repeated measures GLM ANOVA of anteroposterior spectral power with main factors “Group”, “Vision” and their factor interactions. The model parameter Group is a Between-Subjects factor and the model parameter Vision is a Within-Subjects variable.

** Repeated measures GLM ANOVA of anteroposterior spectral power with main factors “DBS”, “Vision” and their factor interactions. The model parameters DBS and Vision are Within-Subjects variables.

Table 3. GLM ANOVA analysis of lateral spectral power

Lateral spectral power	Group	Vision	Group x Vision	Group	Vision	Group x Vision	DBS	Vision	DBS x Vision
Position	**Control vs. DBS OFF ***			**Control vs. DBS ON ***			**DBS OFF vs DBS ON ****		
Head									
0 - 4 Hz	0.863 [0.0]	0.137 [2.4]	0.404 [0.7]	0.259 [1.3]	0.464 [0.6]	0.995 [0.0]	**0.025 [7.5]**	**0.067 [4.5]**	0.154 [2.5]
4 - 7 Hz	**0.006 [8.9]**	0.780 [0.1]	**0.059 [3.9]**	0.198 [1.7]	**0.047 [4.4]**	0.523 [0.4]	**0.037 [6.2]**	0.516 [0.5]	0.259 [1.5]
7 - 25 Hz	**<0.001 [21.8]**	0.363 [0.9]	0.204 [1.7]	**<0.001 [29.1]**	**0.065 [3.7]**	0.201 [1.7]	0.386 [0.8]	0.594 [0.3]	0.332 [1.1]
Shoulder									
0 - 4 Hz	0.836 [0.0]	0.140 [2.3]	0.503 [0.5]	0.236 [1.5]	0.383 [0.8]	0.990 [0.0]	**0.078 [4.1]**	0.163 [2.4]	**0.075 [4.2]**
4 - 7 Hz	0.552 [0.4]	0.761 [0.1]	**0.067 [3.7]**	**0.085 [3.2]**	**0.093 [3.0]**	0.359 [0.9]	**0.031 [6.9]**	0.452 [0.6]	0.296 [1.2]
7 - 25 Hz	0.958 [0.0]	0.732 [0.1]	0.109 [2.8]	0.172 [2.0]	0.204 [1.7]	0.345 [0.9]	**0.028 [7.2]**	0.447 [0.6]	0.149 [2.6]
Hip									
0 - 4 Hz	0.946 [0.0]	0.394 [0.8]	0.785 [0.1]	0.420 [0.7]	0.426 [0.7]	0.885 [0.0]	0.139 [2.8]	0.420 [0.7]	0.320 [1.1]
4 - 7 Hz	0.546 [0.4]	0.285 [1.2]	0.948 [0.0]	**0.002 [12.7]**	0.125 [2.5]	0.927 [0.0]	**0.088 [3.9]**	0.553 [0.4]	0.712 [0.1]
7 - 25 Hz	0.626 [0.2]	0.234 [1.5]	0.401 [0.7]	**<0.001 [18.6]**	0.863 [0.0]	0.383 [0.8]	0.156 [2.5]	0.567 [0.4]	0.316 [1.2]
Knee									
0 - 4 Hz	0.893 [0.0]	0.249 [1.4]	0.662 [0.2]	0.435 [0.6]	0.635 [0.2]	0.813 [0.1]	0.239 [1.7]	0.623 [0.3]	0.226 [1.8]
4 - 7 Hz	0.591 [0.3]	0.519 [0.4]	0.115 [2.7]	0.424 [0.7]	**0.056 [4.1]**	0.783 [0.1]	0.382 [0.9]	0.669 [0.2]	0.380 [0.9]
7 - 25 Hz	0.770 [0.1]	0.335 [1.0]	0.442 [0.6]	0.339 [1.0]	**0.095 [3.0]**	0.984 [0.0]	0.490 [0.5]	0.373 [0.9]	0.573 [0.3]

* Repeated measures GLM ANOVA of lateral spectral power with main factors “Group”, “Vision” and their factor interactions. The model parameter Group is a Between-Subjects factor and the model parameter Vision is a Within-Subjects variable.

** Repeated measures GLM ANOVA of lateral spectral power with main factors “DBS”, “Vision” and their factor interactions. The model parameters DBS and Vision are Within-Subjects variables.

Table 4. GLM ANOVA analysis of segmental spectral power distribution

Spectral power	Vision	Segment	Vision x Segment	Vision	Segment	Vision x Segment	Vision	Segment	Vision x Segment
Position	**DBS OFF ***			**DBS ON ***			**Control ***		
Anteroposterior									
0 - 4 Hz	0.311 [1.2]	**0.034 [6.9]**	0.219 [1.8]	0.430 [0.7]	**0.001 [23.4]**	0.274 [1.4]	**0.051 [4.5]**	**<0.001 [28.1]**	0.168 [2.1]
4 - 7 Hz	0.237 [1.7]	**0.079 [4.2]**	0.237 [1.7]	0.267 [1.4]	**0.029 [7.1]**	0.230 [1.7]	0.381 [0.8]	**0.001 [16.0]**	0.344 [1.0]
7 - 25 Hz	0.843 [0.0]	**0.017 [9.7]**	0.272 [1.4]	0.672 [0.2]	**<0.001 [35.0]**	0.355 [1.0]	0.477 [0.5]	**0.004 [11.9]**	0.658 [0.2]
Lateral									
0 - 4 Hz	0.678 [0.2]	**0.043 [6.1]**	0.558 [0.4]	0.575 [0.3]	**0.025 [7.6]**	0.325 [1.1]	0.945 [0.0]	**0.003 [13.3]**	0.362 [0.9]
4 - 7 Hz	0.467 [0.6]	0.170 [2.3]	0.282 [1.4]	0.137 [2.7]	**0.003 [18.4]**	0.203 [1.9]	**0.061 [4.2]**	**0.036 [5.4]**	0.154 [2.3]
7 - 25 Hz	0.609 [0.3]	0.290 [1.3]	0.177 [2.3]	**0.072 [4.3]**	**<0.001 [56.2]**	**0.074 [4.2]**	0.166 [2.1]	**0.017 [7.3]**	0.197 [1.8]

* Repeated measures GLM ANOVA of anteroposterior and lateral spectral power with main factors “Vision”, “Segment” and their factor interactions. The model parameters Vision and Segment are Within-Subjects variables.

Figure legends

Figure 1. Spectral power of anteroposterior Head, Shoulder, Hip and Knee movements in patients with PD with DBS OFF and DBS ON and in a Control group, across three frequency bands; 0-4 Hz, 4-7 Hz and 7-25 Hz and when standing with eyes closed and eyes open.

Figure 2. Spectral power of lateral Head, Shoulder, Hip and Knee movements in patients with PD with DBS OFF and DBS ON and in a Control group, across three frequency bands; 0-4 Hz, 4-7 Hz and 7-25 Hz and when standing with eyes closed and eyes open.

Figure 3. Schematic view of segmental spectral power distribution in A: Anteroposterior and B: Lateral directions. The black horizontal lines marks whether power distribution was determined as either decreasing on segmental levels from up-down, from down-up or unspecific in the statistical evaluations within the different spectral ranges.

Figures

Figure 1.

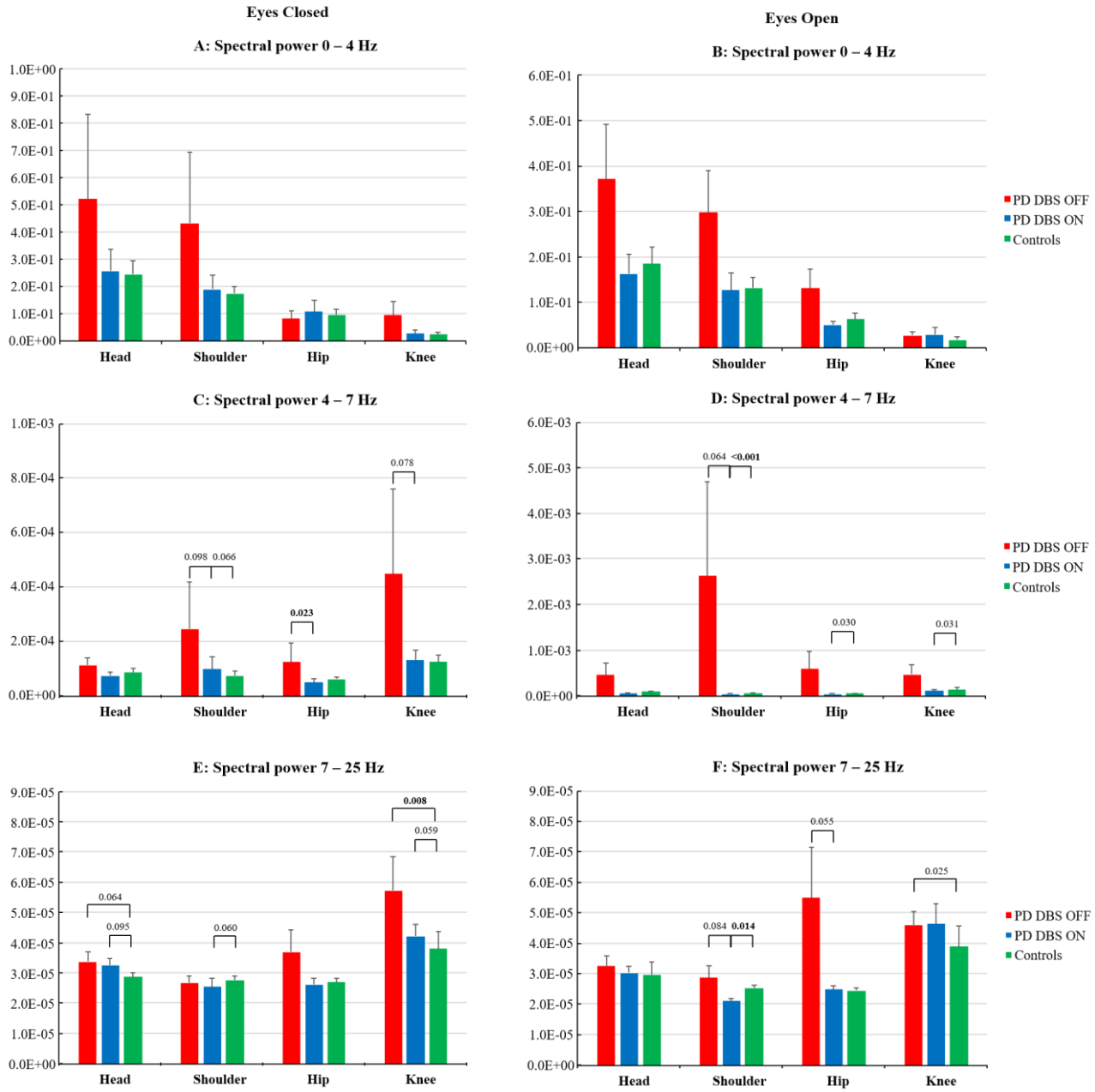


Figure 2.

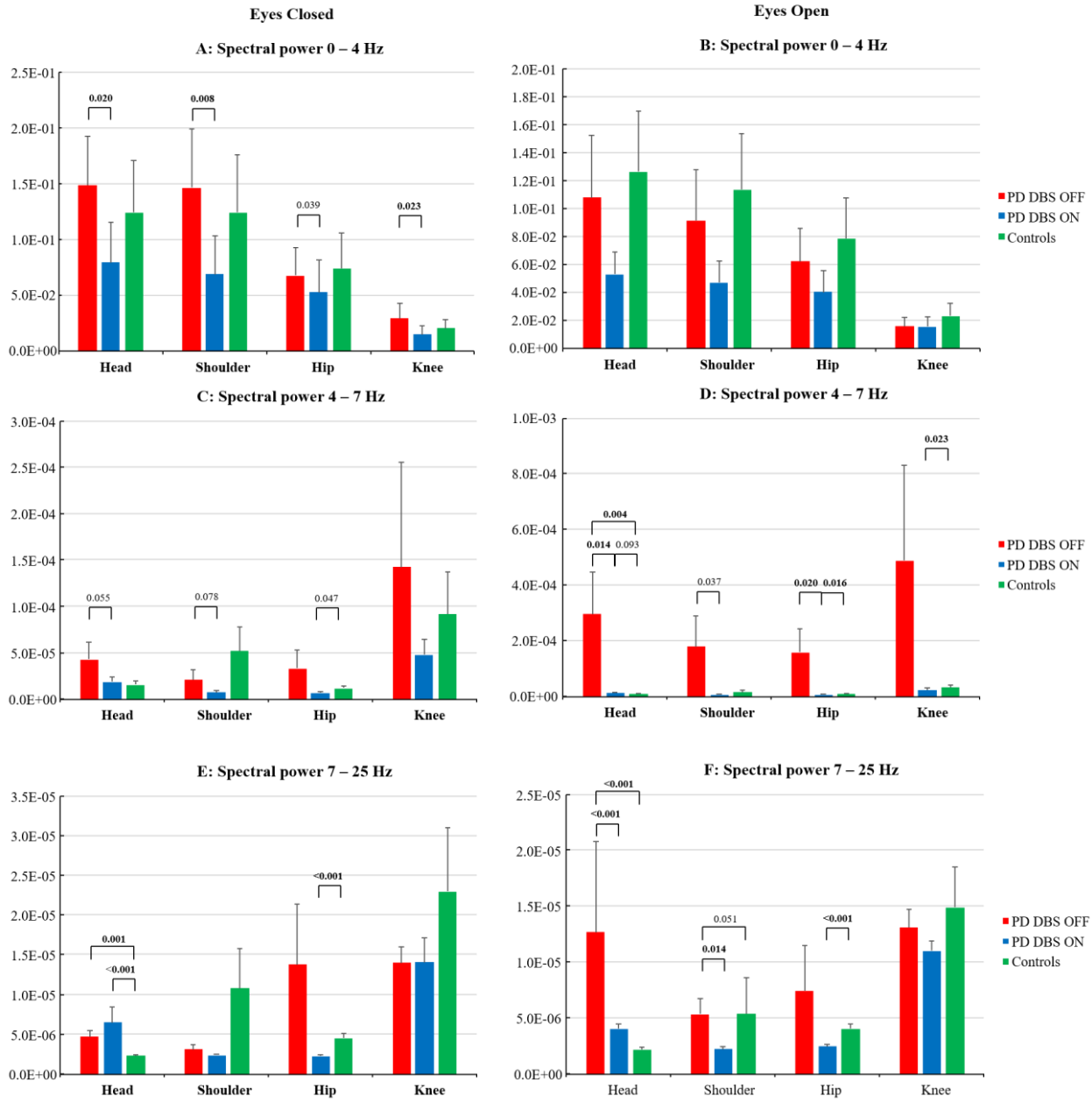
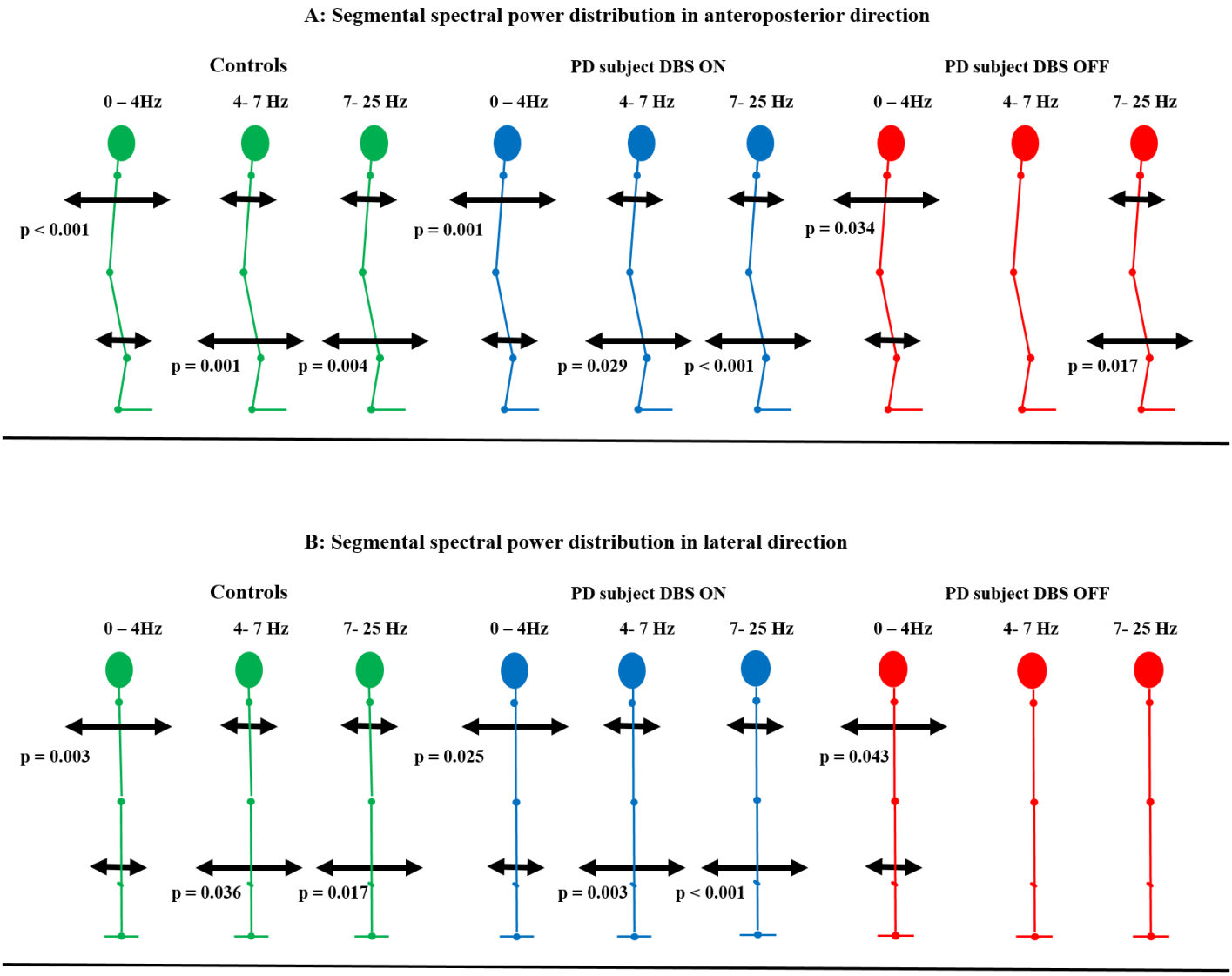

Eyes Closed
A: Spectral power 0 – 4 Hz
2.5E-01
2.0E-01
1.5E-01
1.0E-01
5.0E-02
0.0E+00
0.020
0.008
0.039
0.023
Head
Shoulder
Hip
Knee
Eyes Open
B: Spectral power 0 – 4 Hz
2.0E-01
1.8E-01
1.6E-01
1.4E-01
1.2E-01
1.0E-01
8.0E-02
6.0E-02
4.0E-02
2.0E-02
0.0E+00
Head
Shoulder
Hip
Knee
PD DBS OFF
PD DBS ON
Controls
C: Spectral power 4 – 7 Hz
3.0E-04
2.5E-04
2.0E-04
1.5E-04
1.0E-04
5.0E-05
0.0E+00
0.055
0.078
0.047
Head
Shoulder
Hip
Knee
D: Spectral power 4 – 7 Hz
1.0E-03
8.0E-04
6.0E-04
4.0E-04
2.0E-04
0.0E+00
0.004
0.014
0.093
0.037
0.020
0.016
0.023
Head
Shoulder
Hip
Knee
PD DBS OFF
PD DBS ON
Controls
E: Spectral power 7 – 25 Hz
3.5E-05
3.0E-05
2.5E-05
2.0E-05
1.5E-05
1.0E-05
5.0E-06
0.0E+00
0.001
<0.001
<0.001
Head
Shoulder
Hip
Knee
F: Spectral power 7 – 25 Hz
2.5E-05
2.0E-05
1.5E-05
1.0E-05
5.0E-06
0.0E+00
<0.001
<0.001
0.051
0.014
<0.001
Head
Shoulder
Hip
Knee
PD DBS OFF
PD DBS ON
Controls

Figure 3.


A: Segmental spectral power distribution in anteroposterior direction
Controls
PD subject DBS ON
PD subject DBS OFF
0 – 4Hz
4- 7 Hz
7- 25 Hz
0 – 4Hz
4- 7 Hz
7- 25 Hz
0 – 4Hz
4- 7 Hz
7- 25 Hz
p < 0.001
p = 0.001
p = 0.004
p = 0.001
p = 0.029
p < 0.001
p = 0.034
p = 0.017
B: Segmental spectral power distribution in lateral direction
Controls
PD subject DBS ON
PD subject DBS OFF
0 – 4Hz
4- 7 Hz
7- 25 Hz
0 – 4Hz
4- 7 Hz
7- 25 Hz
0 – 4Hz
4- 7 Hz
7- 25 Hz
p = 0.003
p = 0.036
p = 0.017
p = 0.025
p = 0.003
p < 0.001
p = 0.043