

Modeling and Optimizing Deep Brain Stimulation  
to Enhance Gait in Parkinson's Disease:  
Personalized Treatment with Neurophysiological  
Insights

Hamid Fekri Azgomi<sup>1</sup>, Kenneth H. Louie<sup>1</sup>, Jessica E. Bath<sup>1,2</sup>,  
Kara N. Presbrey<sup>1</sup>, Jannine P. Balakid<sup>1</sup>, Jacob H. Marks<sup>1</sup>,  
Thomas A. Wozny<sup>1</sup>, Nicholas B. Galifianakis<sup>3</sup>,  
Marta San Luciano<sup>3</sup>, Simon Little<sup>3</sup>, Philip A. Starr<sup>1</sup>,  
Doris D. Wang<sup>1</sup>

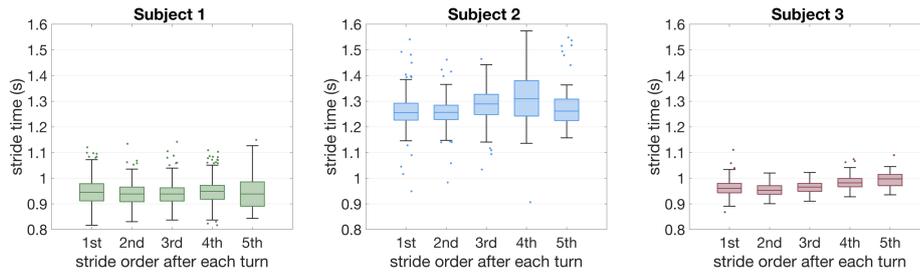
<sup>1</sup>Department of Neurological Surgery.

<sup>2</sup>Department of Physical Therapy and Rehabilitation Science.

<sup>3</sup>Department of Neurology,  
University of California San Francisco, California, USA.

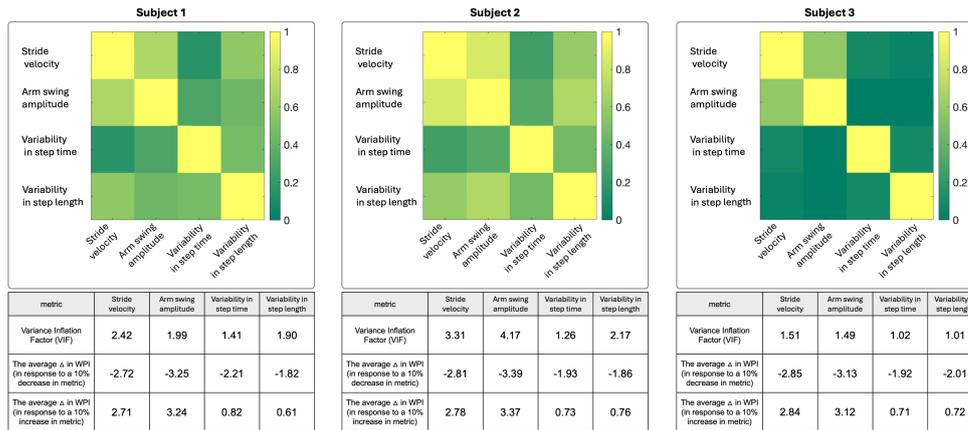
## Supplementary materials

Supplementary Figures [1.](#) - [12.](#) are presented as supplementary information.



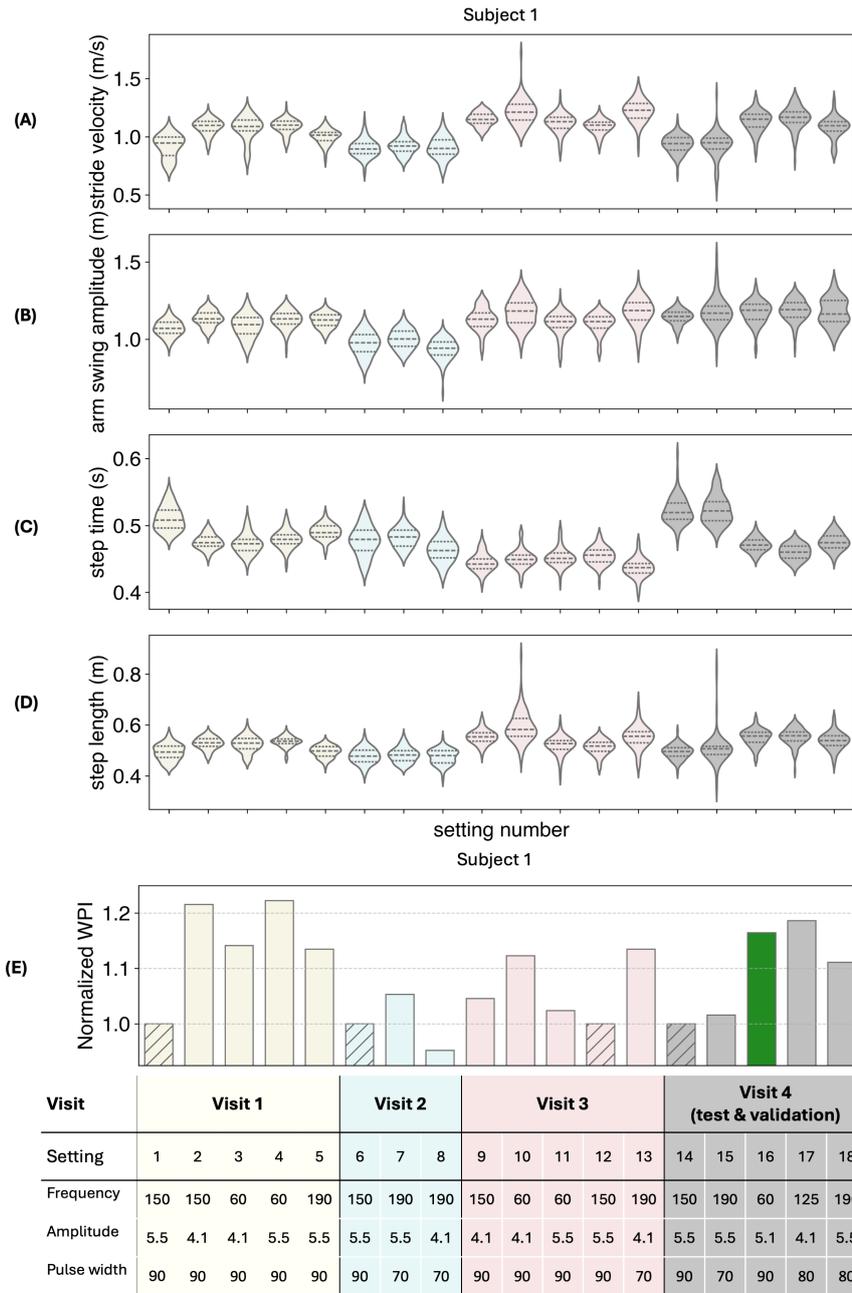
**Supplementary Figure 1. Stride time consistency across stride orders during a 6-meter walk**

Each panel represents an individual participant. Boxplots display the distribution of stride times categorized by stride order during a 6-meter overground walk. The x-axis denotes the different stride orders, while the y-axis indicates stride time in seconds.



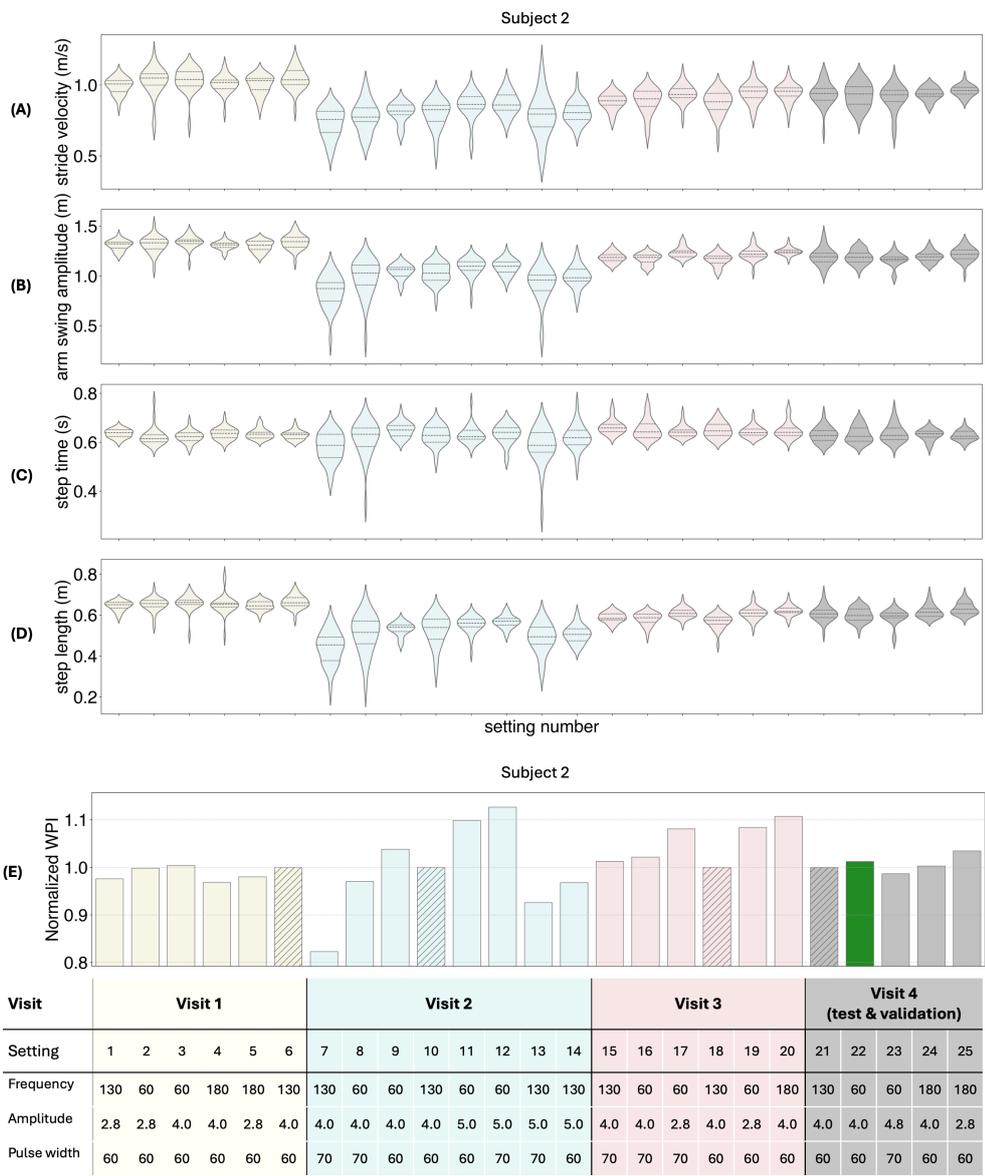
**Supplementary Figure 2. Correlation, variance, and sensitivity analysis of gait metrics with WPI for each participant**

Each panel displays the pairwise Pearson correlation coefficients among all gait metrics and the WPI for an individual participant. The matrix visualizes the degree of linear relationships between variables, with color intensity representing the strength of the correlations: colors range from green (lower values) to yellow (higher values). The low off-diagonal values (green shades) indicate minimal multicollinearity among the metrics, confirming that each metric provides unique and independent information contributing to the WPI. Additionally, each panel includes a table presenting the results of variance inflation factor (VIF) analysis and a sensitivity investigation. The sensitivity analysis was performed by applying a  $\pm 10\%$  change to each metric to assess their impact on the WPI.



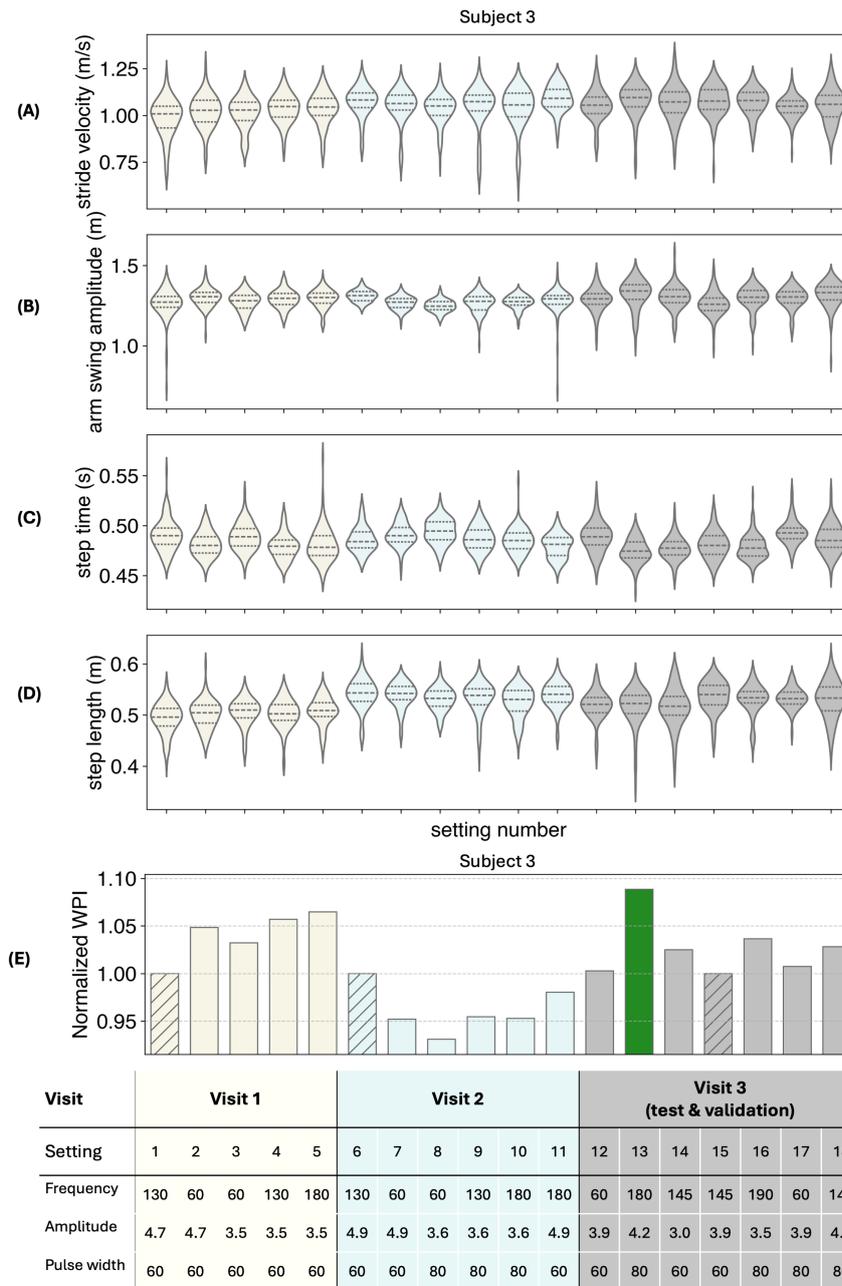
Supplementary Figure 3. Impact of DBS setting adjustments on gait kinematics and walking performance (subject 1).

Panels **(A)**-**(D)** illustrate the variations in gait kinematics as a response to different DBS settings across three visits, measured by **(A)** stride velocity, **(B)** arm swing amplitude, **(C)** step length variability, and **(D)** step time variability. Panel **(E)** displays the corresponding changes in the walking performance index (WPI). Columns with hatched patterns represent the clinically optimized DBS settings tested at each visit. In Visit 4, the green-colored bars correspond to the DBS settings predicted by the Gaussian Process Regression (GPR) model to enhance walking performance. The detailed stimulation parameters for each setting are summarized in the table at the bottom, with each color representing data from a specific visit.



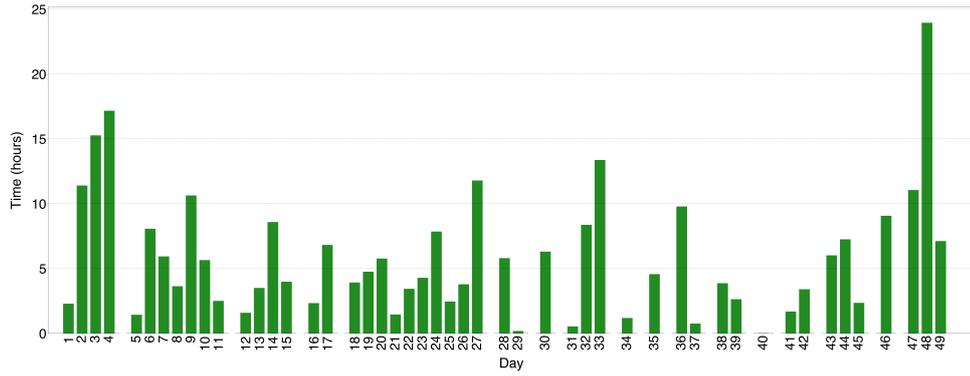
**Supplementary Figure 4. Impact of DBS setting adjustments on gait kinematics and walking performance (subject 2).**

Panels **(A)**-**(D)** illustrate the variations in gait kinematics as a response to different DBS settings across three visits, measured by **(A)** stride velocity, **(B)** arm swing amplitude, **(C)** step length variability, and **(D)** step time variability. Panel **(E)** displays the corresponding changes in the walking performance index (WPI). Columns with hatched patterns represent the clinically optimized DBS settings tested at each visit. In Visit 4, the green-colored bars correspond to the DBS settings predicted by the Gaussian Process Regression (GPR) model to enhance walking performance. The detailed stimulation parameters for each setting are summarized in the table at the bottom, with each color representing data from a specific visit.



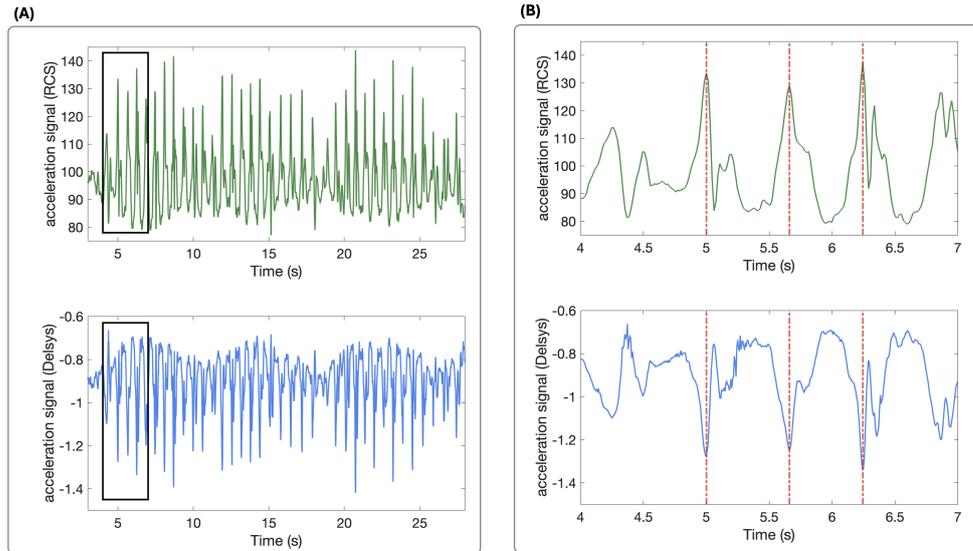
Supplementary Figure 5. Impact of DBS setting adjustments on gait kinematics and walking performance (subject 3).

Panels **(A)**-**(D)** illustrate the variations in gait kinematics as a response to different DBS settings across three visits, measured by **(A)** stride velocity, **(B)** arm swing amplitude, **(C)** step length variability, and **(D)** step time variability. Panel **(E)** displays the corresponding changes in the walking performance index (WPI). Columns with hatched patterns represent the clinically optimized DBS settings tested at each visit. In Visit 3, the green-colored bars correspond to the DBS settings predicted by the Gaussian Process Regression (GPR) model to enhance walking performance. The detailed stimulation parameters for each setting are summarized in the table at the bottom, with each color representing data from a specific visit.



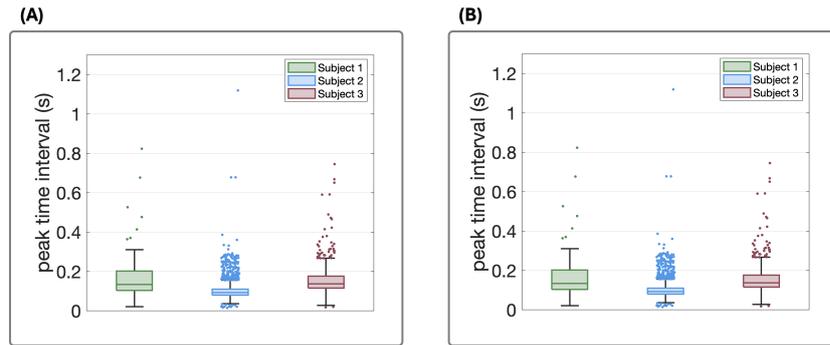
**Supplementary Figure 6. Time spent on gait-optimized setting (subject 1).**

The bar chart illustrates the total time intervals measured across consecutive days. Sequential day numbers are displayed on the x-axis for days with recorded data. Gaps in the data are visually represented by open spaces on the x-axis, indicating periods where no changes to the DBS settings were made. The y-axis represents the total time interval (in hours) for each day.



**Supplementary Figure 7. Synchronization of neural and gait kinematics using peak acceleration moments.**

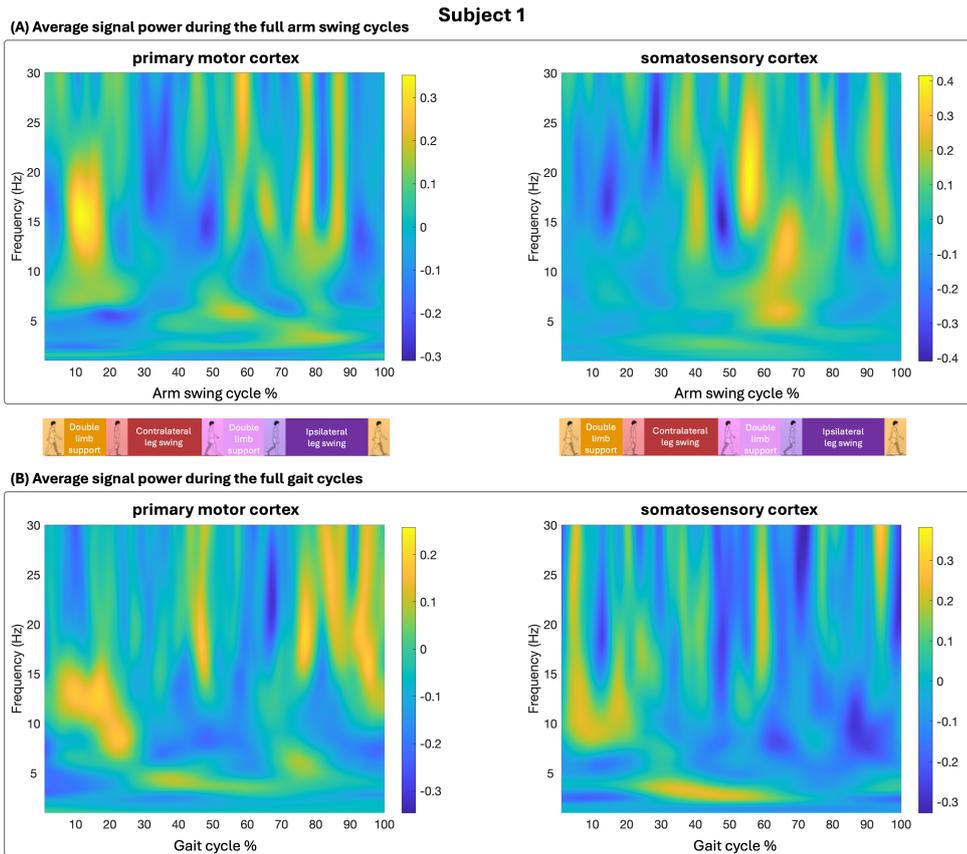
Panel (A) displays a zoomed-out view of acceleration signals recorded during a 6-meter overground walk. The top trace represents data from the RCS device, while the bottom trace shows data from an external chest-mounted accelerometer positioned adjacent to the pulse generator. Panel (B) presents a zoomed-in view of the same acceleration signals, highlighting the peak moments used as temporal anchors for synchronizing neural data with gait kinematics. The alignment of peak accelerations from both devices ensures accurate correspondence between neural activity and gait measurements, validating the reliability of our synchronization method.



**Supplementary Figure 8. Distribution of peak acceleration amplitudes and inter-arrival times across DBS settings.**

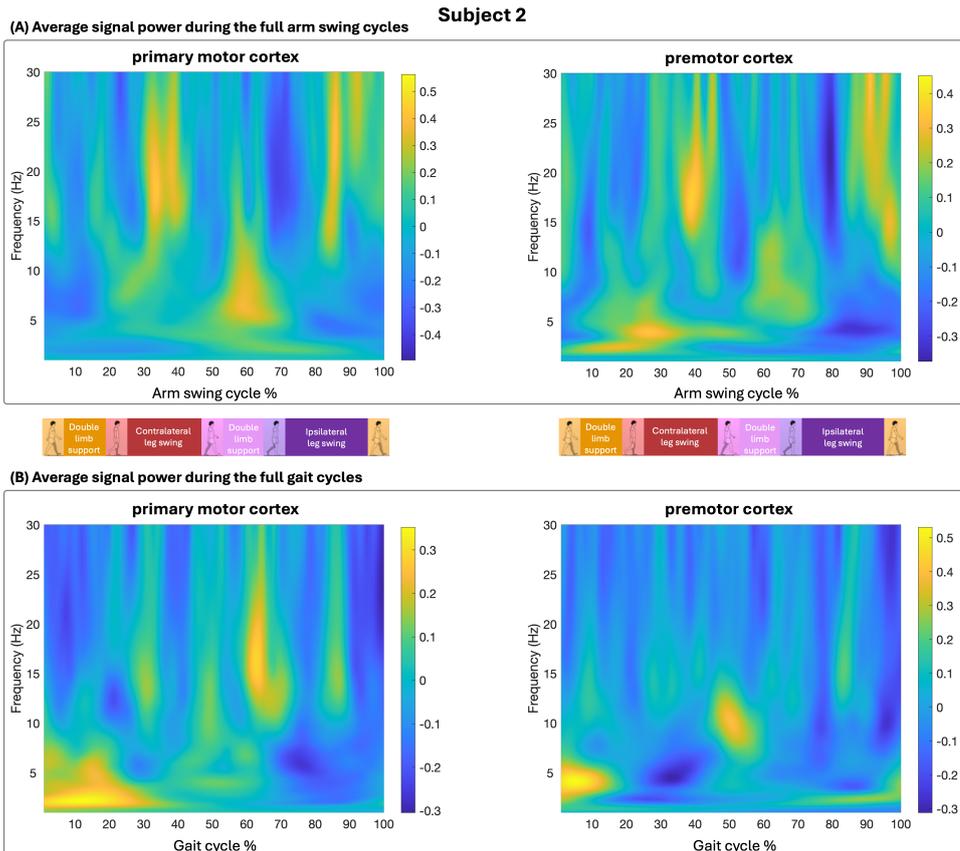
Panel (A) presents boxplots illustrating the distribution of peak acceleration amplitudes across all DBS settings for each participant. Panel (B) displays boxplots of the inter-arrival times between consecutive peak acceleration moments for each participant. Each panel includes three boxplots corresponding to individual participants, highlighting the consistency of peak acceleration patterns across different DBS parameters. The uniform distributions observed in both panels confirm that peak acceleration timing and amplitude remain stable across DBS settings, reinforcing the reliability of our synchronization method.





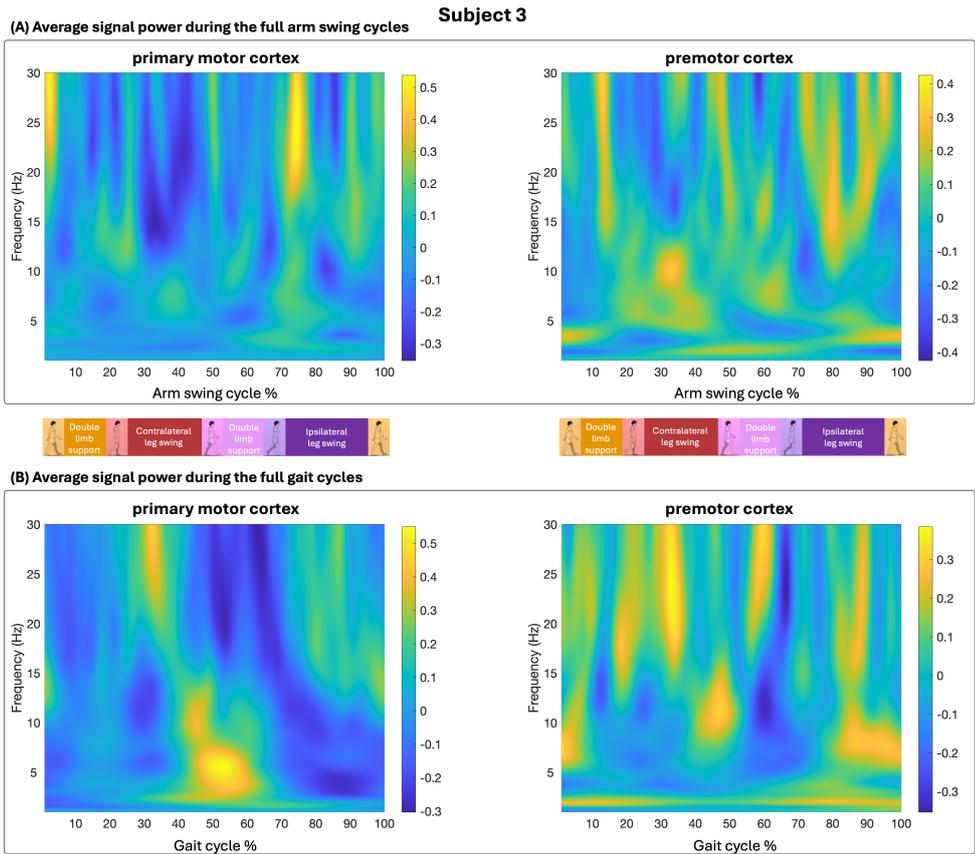
**Supplementary Figure 10. Cortical signal activity during standing arm swings and overground walking (Subject 1).**

Panel (A) displays the average continuous wavelet transform of cortical signals recorded during full arm swing cycles. Panel (B) shows the average continuous wavelet transform of cortical signals recorded across all gait cycles during overground walking. Within each panel, the left and right sub-panels represent data from the primary motor cortex and the somatosensory cortex, respectively. The distinct patterns observed indicate that the cortical electrode strip effectively captures motor activity related to both arm and leg movements during walking.



**Supplementary Figure 11. Cortical signal activity during standing arm swings and overground walking (Subject 2).**

Panel **(A)** displays the average continuous wavelet transform of cortical signals recorded during full arm swing cycles. Panel **(B)** shows the average continuous wavelet transform of cortical signals recorded across all gait cycles during overground walking. Within each panel, the left and right sub-panels represent data from the primary motor cortex and the somatosensory cortex, respectively. The distinct patterns observed indicate that the cortical electrode strip effectively captures motor activity related to both arm and leg movements during walking.



**Supplementary Figure 12. Cortical signal activity during standing arm swings and overground walking (Subject 3).**

Panel (A) displays the average continuous wavelet transform of cortical signals recorded during full arm swing cycles. Panel (B) shows the average continuous wavelet transform of cortical signals recorded across all gait cycles during overground walking. Within each panel, the left and right sub-panels represent data from the primary motor cortex and the somatosensory cortex, respectively. The distinct patterns observed indicate that the cortical electrode strip effectively captures motor activity related to both arm and leg movements during walking.