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Summary

This repository contains MATLAB and NEURON code and data for the following article:

- Wang, B., Aberra, A. S., Grill, W. M., & Peterchev, A. V. (2023). Responses of model cortical neurons to temporal interference stimulation and related transcranial alternating current stimulation modalities. Journal of neural engineering, 19(6), 066023. https://doi.org/10.1088/1741-2552/acab30.

The code simulates neuronal responses to temporal interference stimulation and other related transcranial alternating current stimulation methods. The data covers results in the main text and supplementary figures S4–S13.

Code is adapted from the following publications:

1. Aberra AS, Wang B, Grill WM, Peterchev AV. Simulation of transcranial magnetic stimulation in head model with morphologically-realistic cortical neurons. Brain Stimulation 2020;13:175–89. https://doi.org/10.1016/j.brs.2019.10.002.
2. Aberra AS, Peterchev AV, Grill WM. Biophysically Realistic Neuron Models for Simulation of Cortical Stimulation. J Neural Eng 2018;15:066023. https://doi.org/10.1088/1741-2552/aadbb1.

File and data organization

- **`Data`** folder: contains the NEURON simulation results in binary and text formats (.txt files) and compiled MATLAB format (.mat files).
  - **`.mat`** files: compiled results.
  - **`thresh`** and **`block`** folders: contain results for activation and block threshold searches.
    - **`L5_TTPC2_cADpyr232_1`** folder: contain results layer 5 pyramidal cell (1st clone). If simulation is run with additional cell models, the MATLAB code will generate a subfolder for the models.
      - **`.mat`** files: compiled results of all stimulation methods for a given first electric field (as defined by its orientation).
      - Subfolders in the cell folders are named as FirstEfield_soma_StimType for LFS, HFS, HFS_10, and AM-HFS, and FirstEfield_SecondEfield_EfieldRatio _soma_StimType for TIS, RFS, and AM-HFS. Each subfolder contains
        - **`all_ap_times.txt`**: binary, timing of action potentials fired by all compartments except for the threshold compartment.
        - **`all_ap_netids.txt`**: binary, IDs of compartments firing action potential.
        - **`thresh_cmprt_ap_netids.txt`**: binary, timing of action potentials fired by the threshold compartment.
        - **`thresh_cmprt_times.txt`**: binary, ID of threshold compartment.
        - **`thresh.txt`** or **`block.txt`**: text, threshold of activation or block (V/m), firing rate (Hz), average spike count per burst, number of burst, spikes for each burst.

- **data.mat**: compiled data from **thresh.txt** or **block.txt**.
- **APtimes.mat**: compiled data the binary action potential files.

Data related to Fig. 4A and 4B are in the folders:

- **thresh\L5_TTPC2_cADpyr232_1\theta1_131.8_phi1_60.0_theta2_90.0_phi2_0.0_ratio_1_soma_TIS_10_2k:**
- **block\L5_TTPC2_cADpyr232_1\theta1_131.8_phi1_60.0_theta2_90.0_phi2_0.0_ratio_1_soma_TIS_10_2k\block_test**
  - **tvec.txt**: binary, time vector written by NEURON.
  - **vm_data_bin.txt**: binary, transmembrane potentials written by NEURON.
  - **Vm.mat**: compiled data including time vector and transmembrane potentials.

- **mat** folder: containing the MATLAB code that set ups the NEURON simulations, processes the simulation results (text and binary files, in .txt format), and compiles the data into .mat format for further analysis and visualization.
  - **main_func_1D.m**: main function for running simulation using low frequency stimulation (LFS), high frequency stimulation (HFS), and amplitude modulated HFS (AM-HFS). Input arguments are the cell id (see **cellmodelnames.m**), id of orientation (1 to 16), and simulation type ('thresh' orblock').
  - **main_func_3D_TIS.m**: main function for running simulation using temporal interference stimulation (TIS).
  - **main_func_3D_RFS.m**: main function for running simulation using rotational field (high frequency) stimulation (RFS).
  - **main_func_3D_AM_RFS.m**: main function for running simulation using amplitude modulated RFS (AM-RFS).
  - **load_params.m**: load most simulation parameters that are common for the different stimulation methods.
  - **cellmodelnames.m**: cell name for a given cell id.
  - **default_v_inits.m**: default transmembrane potential for a given cell.
  - **output_morph_params.m**: settings for morphological adjustment in the NEURON code.
  - **Efield_orientation.m**: vector of electric field orientations (in spherical coordinates)
  - **revert_field.m**: reverse a field orientation.
  - **TACS_wave.m**: time vector and waveform(s) of the electric field(s).
  - **current_wave.m**: current waveform for testing block.
  - **switch_1D.m**: parallelization of 1D stimulation methods.
  - **run_LFS.m**: parameters of LFS.
  - **run_HFS.m**: parameters of HFS.
  - **run_HFS_10.m**: parameters of HFS with 10 Hz firing rate for threshold determination.
  - **run_AM_HFS.m**: parameters of AM-HFS.
  - **run_1D_stim.m**: run 1D stimulation for given field orientation and reversed direction.
  - **run_TIS.m**: parameters of TIS.
  - **run_RFS.m**: parameters of RFS.
  - **run_AM_RFS.m**: parameters of AM-RFS.
  - **run_3D_stim.m**: parallelization of 3D stimulation methods (combinations of field orientation and ratio).
  - **run_orientation_ratio.m**: run 3D stimulation for combinations of given field orientations and reversed directions.

- **run_nrn_thresh.m**: prepare and run NEURON simulations for activation threshold search and process data.
- **run_nrn_block.m**: prepare and run NEURON simulations for block threshold search and process data.
- **create_mat_data_folder.m**: create folder for storing MATLAB data.
- **create_nrn_folder.m**: create temporary folder for storing NEURON data.
- **analyze_spike_time.m**: analyzed timing of action potentials
- **save_data.m**: save data obtained from activation threshold search.
- **save_data_block.m**: save data obtained from block threshold search.
- **nrn_vread.m**: read binary file written by NEURON.
- **write_vector_bin.m**: write binary file for NEURON.

- **nrn** folder: containing the NEURON hoc code for simulating the neural response.
  - **cells** folder: containing the Blue Brain neuron models.
  - **Mod_files** folder: containing the membrane mechanisms .mod files.
  - **coords** folder: folder for writing the coordinates files of the neuron models.
  - **init_TIS_stim.hoc**: loading all hoc files to prepare the simulation.
  - **init_TIS_stim_cluster.hoc**: loading all hoc files to prepare the simulation, cluster version.
  - **defvars.hoc**: definition of variables and objects.
  - **O2d.hoc**: 2d object array.
  - **getParams.hoc**: load parameters from files written by MATLAB code.
  - **ssprocinit.hoc**: steady state initialization of neuron transmembrane potential.
  - **interp_coordinates.hoc**: set coordinates and topology of neuron model.
  - **cell_chooser.hoc**: choose neuron model from library of cells.
  - **edit_morphology.hoc**: functions for modification of neural morphology.
  - **myelin_biophysics.hoc**: functions for adjusting the properties of myelin.
  - **get_es.hoc**: calculate extracellular potentials.
  - **stim_wave_import.hoc**: import stimulation waveforms of electric field and current injection.
  - **saveDatavector.hoc**: functions for saving vector(s).
  - **threshold_finder.hoc**: function for finding neural activation threshold.
  - **block_threshold_finder.hoc**: function for finding neural block threshold.
  - **block_threshold_finder_wfilt.hoc**: function for finding neural block threshold using filtered transmembrane potential.
  - **init_save_record.hoc**: functions for initializing objects for recording action potentials and transmembrane potential and for saving the results.
  - **run_stim.hoc**: function for running threshold searches.