Patient-specific modeling

Tool development & applications to niSCS

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SCS

- Well established in pain management
- Emerging applications: including rehabilitation
- Limitations wrt access, risk, reintervention, etc.

niSCS

- Noninvasive option would overcome many issues
- Removes interventional risk, reintervention, etc.
- Far greater access
  - Non-invasive trialing
  - Non-invasive rehabilitation options

Question

- Unclear if niSCS feasible
  - Some reports: limited methodology, vague outcomes
  - Some modeling: very simplistic, unconvincing metrics
- Answer required detailed, accurate models
  - Individual anatomy influences E-field
  - Precise models would allow individualised targeting
  - Potential applications to other areas

Image to model

- Derive detailed patient-specific models from clinical imaging
- Image $\mapsto$ FEM $\mapsto V(x, y, z)$
- Technique:
  - Map in electrodes
  - Form mesh
  - Apply physics
  - Solve for V

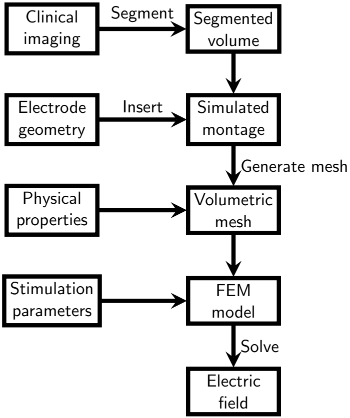


Figure: Flowchart of implemented method.

Image segmentation

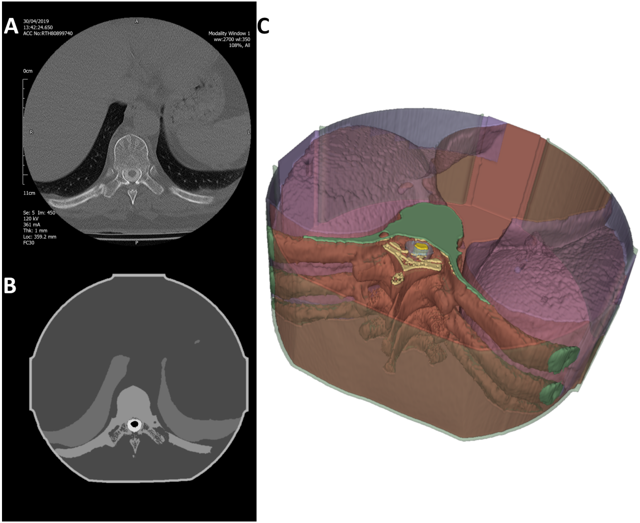


Figure: Image derived model

Electrodes & meshing

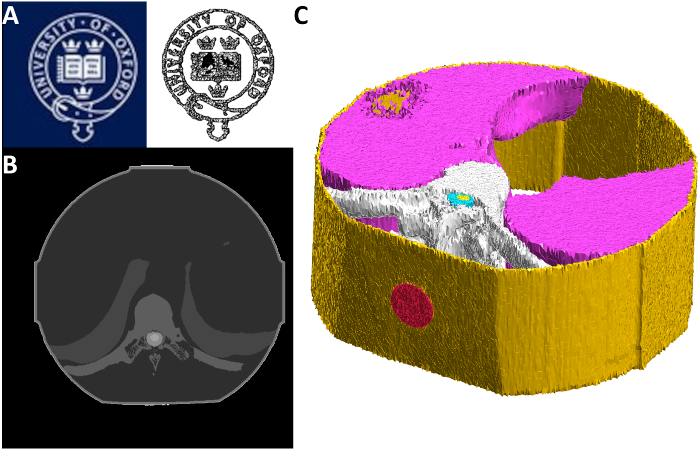


Figure: Mesh from imaging

Solving models

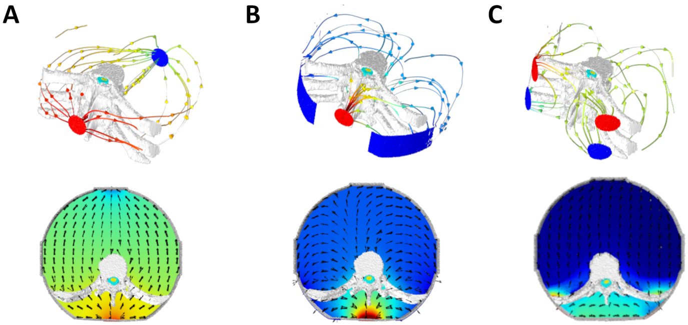


Figure: Results: $V(x, y, z)$ & $\vec{E}$

What to do with V?

- Can solve for field in complex patient-specific anatomy
- But what next?
  - Unintuitive visualisation
  - Metrics divorced from physiology

Visualisation

- $f : (x, y, z) \rightarrow V$
- Interpolate slices, etc.
- Visualise results as overlay
- Extends to any metric

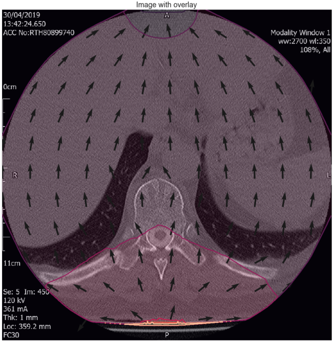


Figure: Axial slice with overlay

Activating function

- Electric field produced by stimulation experienced by neurons that pass through it
- We aim to create an electric field that influences neural activity in useful ways
- We need to link the external field to neural activity to make useful models
- Approximations exist: activating function!
  - The external electric field drives a transmembrane current
  - This current results in membrane potential changes & (hopefully) action potential initiation
  - This inward current is related to the rate of change of the external field
  - Where there is more current flow into a point than out of it, this drives current into the cell
- There are challenges to generalising this to 3D, realistic fields
  - But we can do it now!
  - Can compute AF for any given orientation in 3D space to predict activation

A generalised activating function

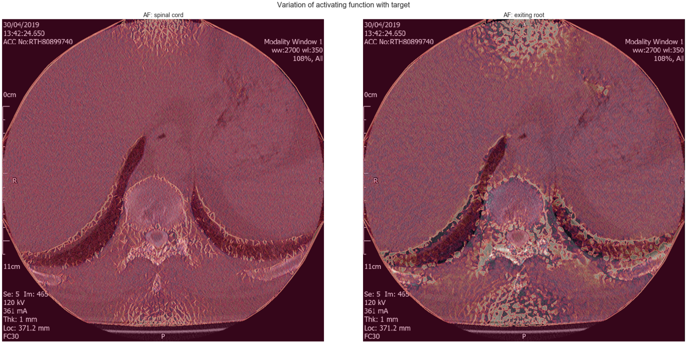


Figure: Activation function, spinal cord vs. spinal root

Axon models

- AF still an approximation
- Full biophysical model: most physiologically accurate
- Need to "place" axon in model space
  - Method developed: axon model with explicit mapping to 3D model
  - Requires "trajectory" to map to in 3D
  - ... but we can also compute that!

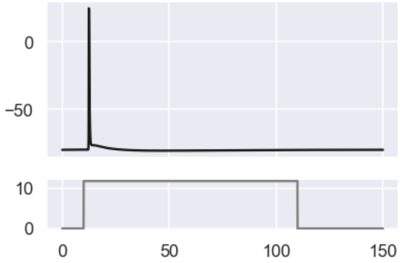


Figure: Action potential generation by simulated stimulation

Axon trajectories

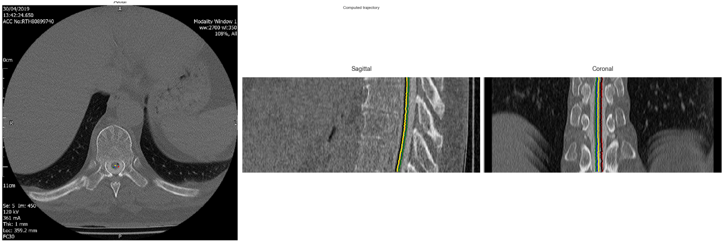


Figure: Example axon trajectories

Abstraction

- Useful methods: anatomically & physiologically realistic models
- Entirely patient-specific
- Can simulate electrode placement & effects of stimulation
- Complex to implement!
  - Methods generalised & packaged
  - Can get patient-specific models direct from clinical imaging
  - Can create computational models & 3D printed models for validation

GUI

- Graphical interface
- Allows easy model specification
- No knowledge of underlying implementation necessary
- Specify image volume, electrode geometry & stimulation parameters
- Automatically creates & solves model
- More complex biophysics & extended functions being added to GUI...

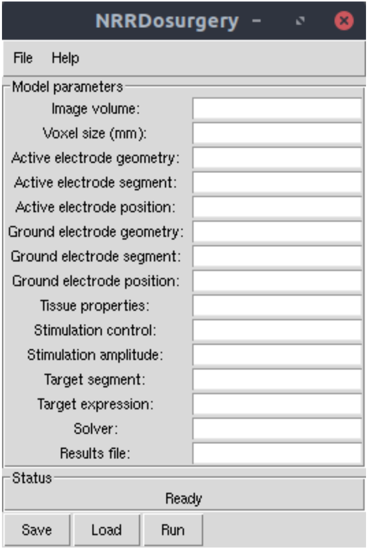


Figure: Graphical interface

Data format

- Standard file format
- Allows reproducibility & easy model specification
- Can directly write to model files
- Directly maps to data structures
- Can use direct programming interface to generate automatically
- Allows algorithmic model iteration! Optimisation of parameters, etc...

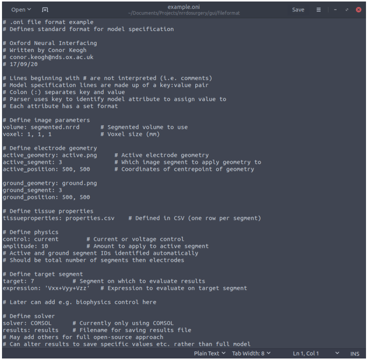


Figure: File specification

Applications

- Lots of fancy methods: need to do something with them...
- Does noninvasive spinal cord stimulation do anything?
  - Simple: 3.2cm diameter round electrode over T11, 30mA DC
  - Interferential: 2 pairs of electrodes lateral to midline; 1kHz & 1.02kHz, 30mA peak

DC stimulation

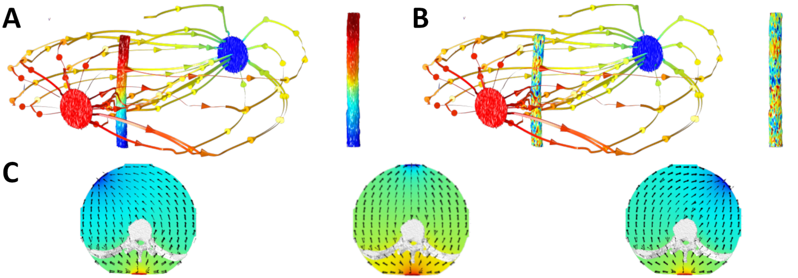


Figure: DC stimulation

DC stimulation

Figure: V & $\vec{E}$, DC stimulation

DC stimulation

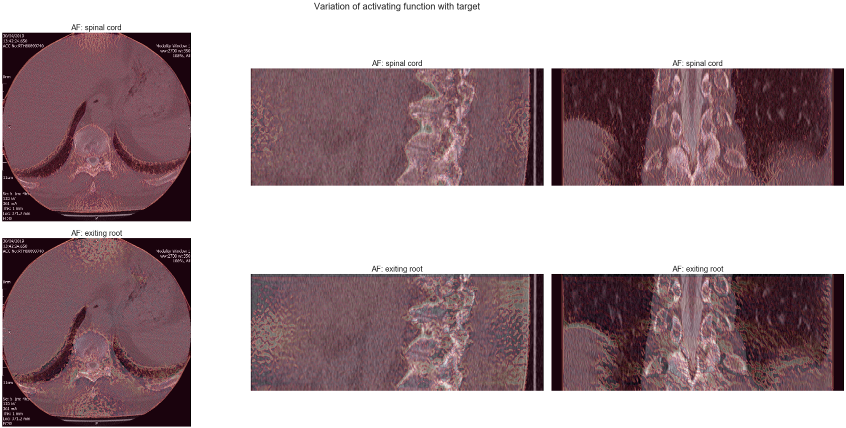
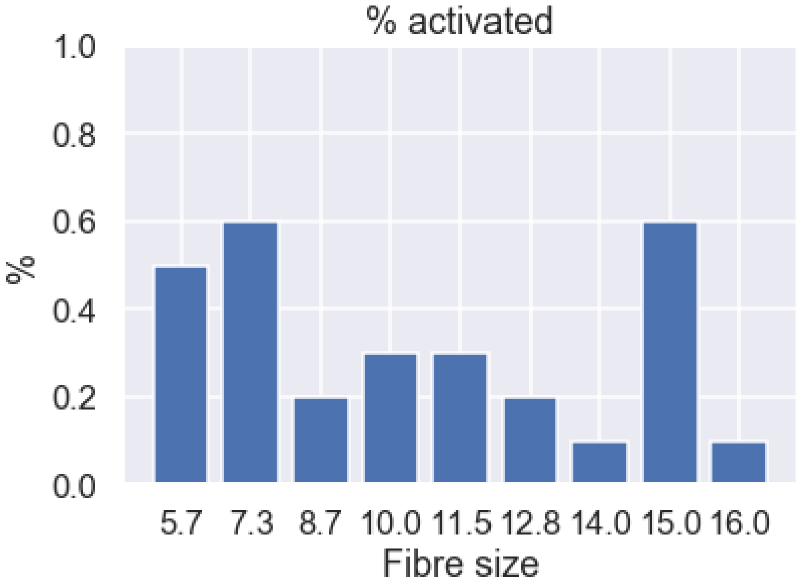


Figure: Activating function, DC stimulation

DC stimulation



DC stimulation

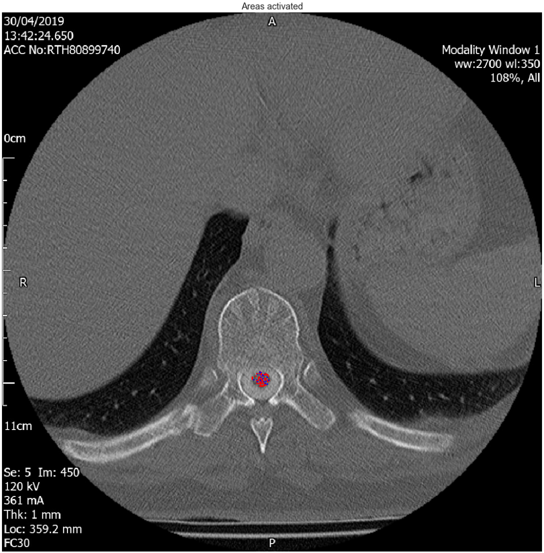


Figure: Distribution of activated vs. unactivated trajectories

Interferential stimulation

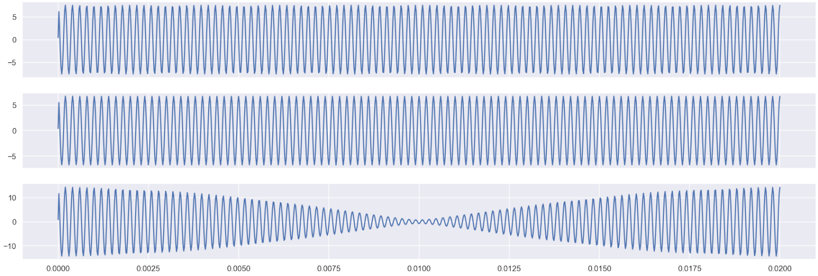


Figure: Time series of V: interferential stimulation

Interferential stimulation

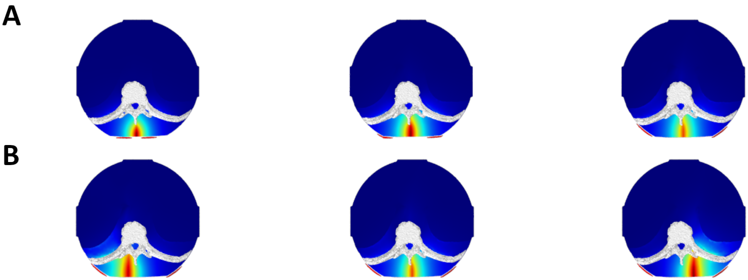


Figure: Interferential: steering

Interferential stimulation

- Activation metrics for interferential in progress
- RAM limited - need to be a bit more clever...

niSCS

- niSCS seems possible
- Generates activation on highly accurate models
- Mechanism needs more modeling: ?spinal roots
- Interferential seems promising: can steer
- Needs more work: ?target areas of cord with steering

Analysis tools

- Tools developed useful
- Provide generalisable way to produce models from imaging
- Simple (to use) methods to get activating function in 3D, link axon models, etc.
- Other application areas...

Next steps

- Validation: printed structures
- Optimisation: maximise activation
- Interface: fit tools into single tool
- Applications: ?priorities