High-Fidelity Controlled-Resolution Atlas and Deformable Model-based Anatomical Modeling for Medical Simulation and Therapy Planning

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Abstract

This poster summarizes work underway on neurosurgery simulation and planning, with an emphasis on anatomical modeling techniques related to segmentation and meshing, while describing plans for therapy modeling. We believe that this research has broad applicability to Computational Neuroscience, Biomechanics and Multiscale Systems Biology. We describe innovations that center on patient-specific representation of the brain, including skull base anatomy, and spine. In general, we advocate a model-based approach to segmentation that leverages a digital atlas of the anatomy which is expressed as a deformable contour or surface mesh model that can be warped to patient image data. Furthermore, in many cases, we proceed in a manner that represents several tissue boundaries at once, whereby an atlas is expressed as a deformable multi-surface 2-Simplex model, which imbeds static collision detection to prevent spatial overlap. We develop a multi-surface Simplex model with an internal force based on statistical shape models (SSMs), with applications to spine segmentation; we are currently applying this technique to simulation-based scoliosis surgery planning. In turn, the dual triangulated surface mesh that results can serve as a first stage for controlled-resolution variational tetrahedralization. Finally, based on this duality between 2-Simplex and triangulated surface, we are currently developing an initialization of the 2-Simplex mesh from a multi-material contouring algorithm of ours, which leads to a 2-Simplex deformable mesh model with shared faces. The application of the latter technique is a shared-face multi-surface mesh of a deep-brain atlas, towards real-time brain shift estimation for robotic deep-brain stimulation that produces continuous deformation across atlas boundaries. We also describe innovations on deformable 3D 1-Simplex contour models that have been applied to identifying the intra-cranial portion of cranial nerves, including the integration of statistical shape models (SSMs) into the deformable contour model. These contour models have a number of planned, feasible extensions for neurological modeling applications.

1. Anatomical modeling – segmentation: deformable models & digital atlases

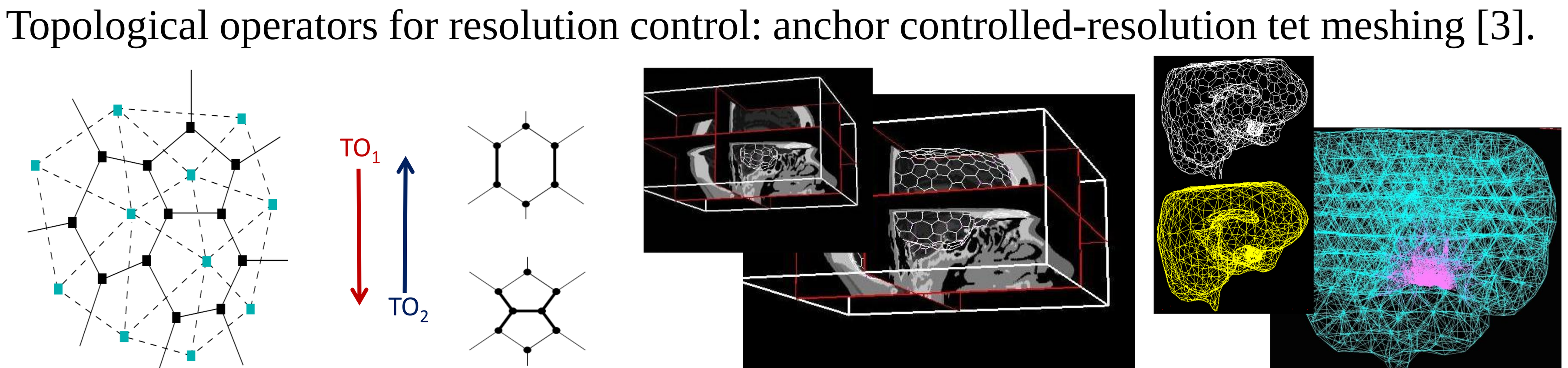
- Anatomical modeling for ***planning*** and ***simulation*** of neuro- and orthopedic surgery.
- Current state-of-the-art: *voxel-based* (bottom-up), *contour/surface-based* (tissue boundary), *atlas-based* segmentation: ***we combine deformable contour/surface models with atlases.***

1.1 Background: Deformable surface and contour models.

- Model with internal and external "forces" to identify boundary or medial axis.
- Emphasis on ***Simplex*** model [1]; N-Simplex: mesh where each vertex has (n+1) neighbors.
- 2-Simplex: 3-connected surface mesh; 1-Simplex: 2-connected 3D contour mesh.
- Newtonian physically based model for vertex motion:

$$m\frac{d^2\boldsymbol{P}_i}{dt^2} = -\gamma\frac{d\boldsymbol{P}_i}{dt} + \alpha\boldsymbol{F}_{int} + \beta\boldsymbol{F}_{ext} \qquad (1)$$

  - External forces: balloon-like inflation & image stopping forces.
  - Internal forces: smoothness (C^1-continuity) & shape statistics compliance.
  - Gilles multi-surface model: static collision detection prevents spatial overlap [2].
- Topological operators for resolution control: anchor controlled-resolution tet meshing [3].



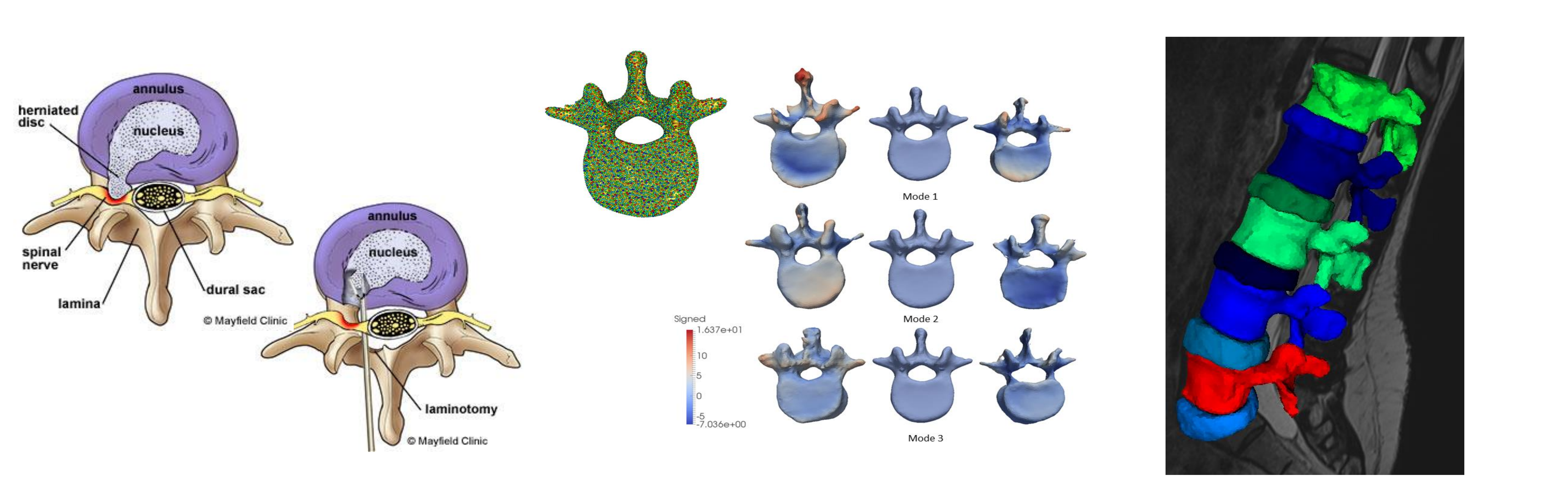
(a) (b) (c) (d)

Figure 1 Simplex model [1]: (a) 3-connectivity and duality with triangular mesh; (b) topological operators. (c) Balloon and image forces. (d) Dual triangulated surface as input to variational controlled-resolution tetrahedral meshing [3].

2. Anatomical modeling for surgery planning and simulation

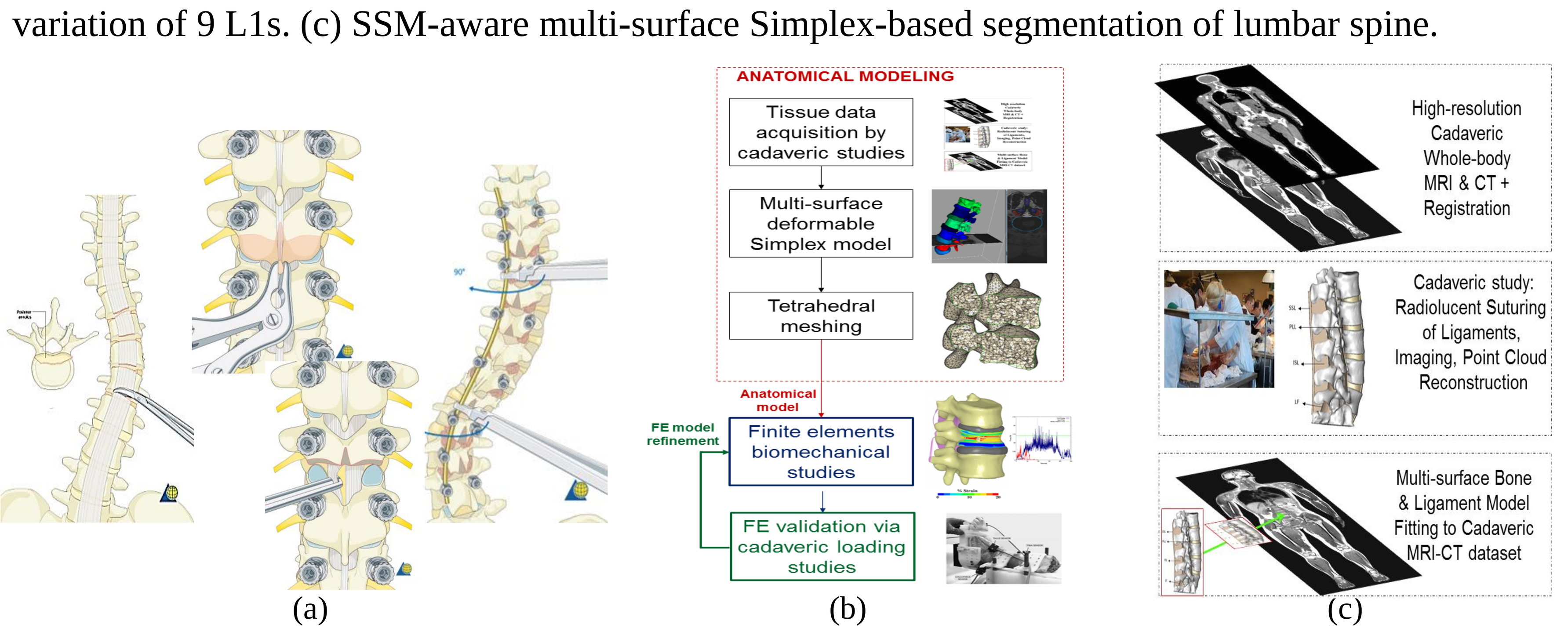
2.1 Spine modeling for discectomy and scoliosis surgery simulation

- Multi-surface 2-simplex (fig. 2) for segmenting ***vertebrae*** and ***intervertebral disc*** [4].
- Integration of shape statistics force within multi-surface Newtonian model [4].
- Shape statistics points via ShapeWorks [5]; Principal Component Analysis via Statismo [6].
- Underway (fig. 3): application of Simplex multi-surface model to scoliosis surgery planning [7]. Cadaveric approach to ligamentoskeletal modeling for finite elements studies.



(a) (b) (c)

Figure 2: Minimally supervised spine segmentation and surgery planning [4]. (a) Discectomy. (b) Shape statistics-based vertebral segmentation: inset- points used for shape correspondence; center: modes of variation of 9 L1s. (c) SSM-aware multi-surface Simplex-based segmentation of lumbar spine.

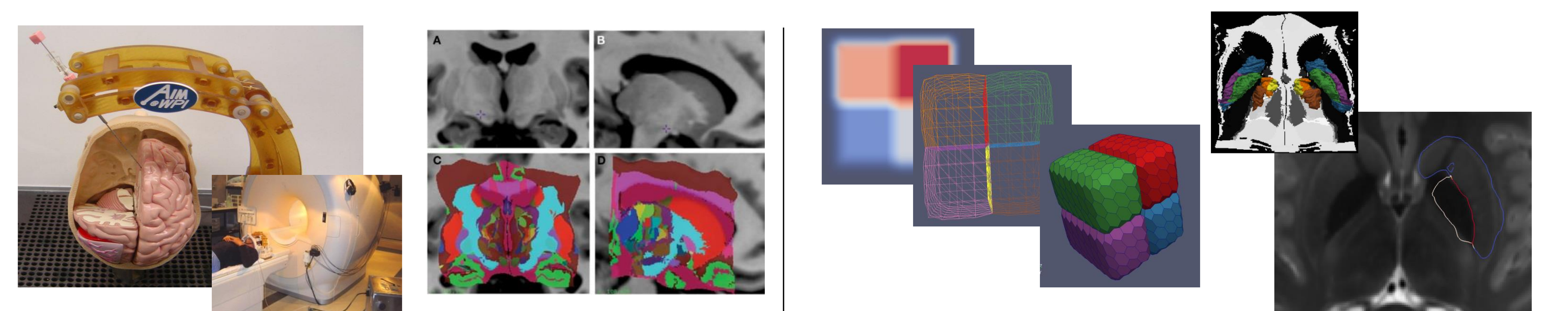


(a) (b) (c)

Figure 3: Proposed extension to scoliosis surgery planning [7]. (a) Important stages of scoliosis surgery: (left) anterior and (middle) posterior release featuring spinal ligament and bony process removal; (right) scoliosis correction through 90-degree rotation of curved rod. (b) Proposed surgery planning approach; (c) details of cadaveric image and spinal surface acquisition approach.

2.2 Atlas-based subcortical models for robotic deep-brain stimulation planning

- Surgery planning for MRI-compatible ***deep-brain stimulation (DBS) robotic assistant*** [8].
- Development of lightweight multi-surface mesh representation of deep-brain atlas [9].
- Multi-surface atlas mesh will be warped to preoperative image data first, then be updated in real-time (~1 Hz) based on intraoperative MRI acquisition for brain shift estimation.
- Multi-surface atlas mesh must have ***shared boundaries***, due to continuity of brain tissue.
- ***Multi-material (MM) contouring*** of shared boundaries of atlas underway; produces shared triangulated surface boundaries of digital atlas (fig. 4), converted to Simplex by duality [10].

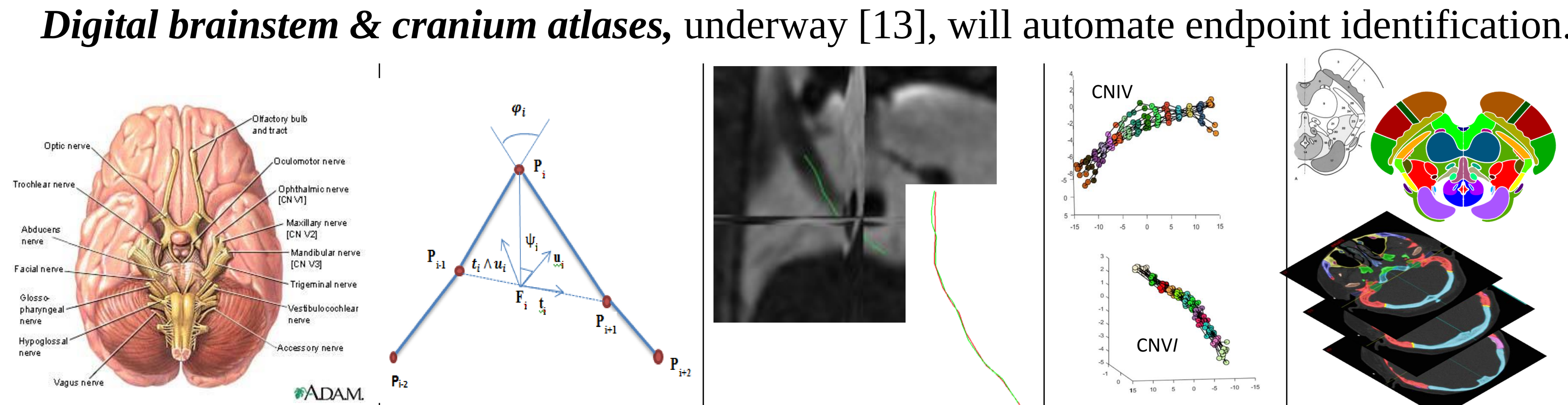


(a) (b)

Figure 4. Atlas-based subcortical models for robotic Deep-Brain Stimulation. (a) Foundational technologies (l. to r.): MRI-compatible DBS robotic assistant (inset: shown on volunteer in scanner); digital deep brain atlas, shown co-registered with MRI data. (b) Multi-material contouring (l. to r.): application to synthetic data (volume, MM contour, dual Simplex mesh) and to deep-brain atlas labels (Striatum & Globus Pallidus at bottom right; full atlas in top left inset).

2.3 1-Simplex-based cranial nerve segmentation and shape statistics

- Segmentation of ***cranial nerves*** for skull base surgery planning and simulation [11].
- Objective: ***1-simplex equivalent*** of multi-surface 2-simplex, while also ***preventing spatial overlap with blood vessels*** (Circle of Willis, etc.) (fig. 5).
- Curvilinear structure: use 3D contours, not surfaces. 1-simplex: 2-connected 3D contour.
- ***Clothesline*** metaphor: nerve path identification facilitated by knowledge of both ends; inner end coincides with brainstem attachment, outer end with foramen in cranium.
- SSM of intracranial portion of cranial nerves [12] integrated in 1-Simplex model.
- ***Digital brainstem & cranium atlases,*** underway [13], will automate endpoint identification.

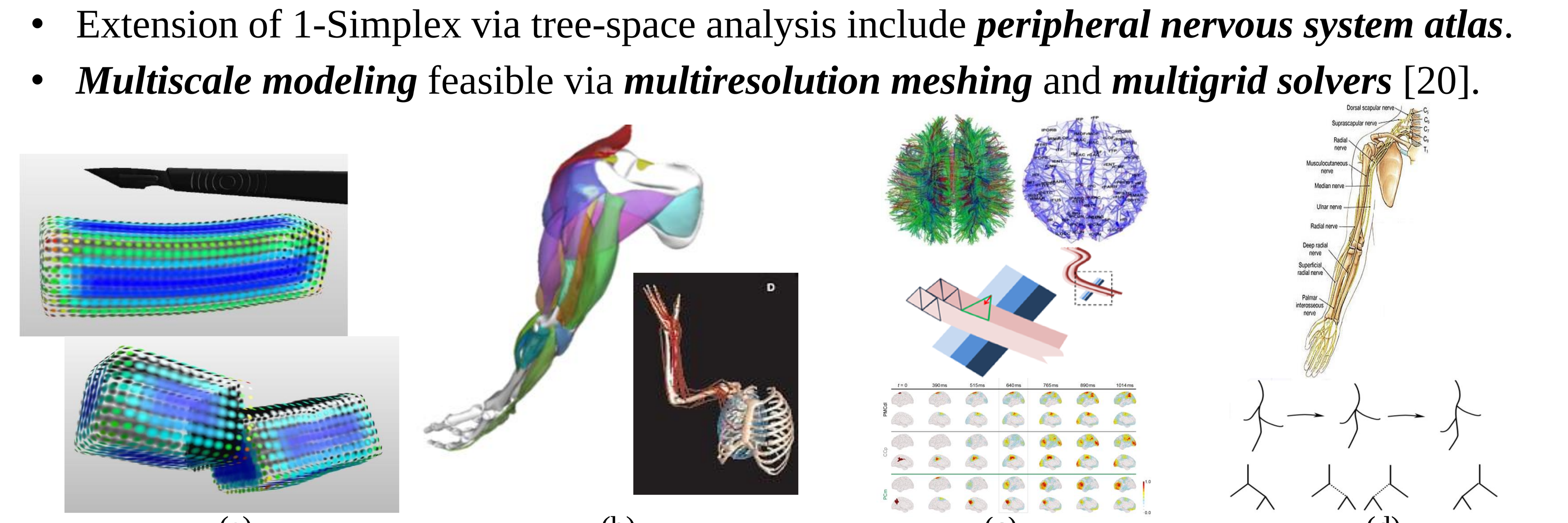


(a) (b) (c) (d) (e)

Figure 5. (a) Cranial nerve modeling (l. to r.): anatomy- 10 pairs of nerves emanating from brainstem, with 2 pairs anterior to brainstem; (b) 1-simplex geometry; preliminary implementation on synthetic data. (b) 1-Simplex 3D contour model, with 2-connectivity. (c) Validation via T2-MRI of oculomotor nerve (vs expert labeling in red). (d) Shape statistics model of cranial nerves, via particle-based optimization in ContourWorks [12]. (e) Digital brainstem and cranium atlases underway.

3. Future Work and Relevance to IMAG Workgroups

- Future work based on integration with ***therapy and function models***, depicted in figure 6.
- Apply ***interactive cutting*** based on Simulation Open Framework Architecture [14] [15].
- ***Personalized musculoskeletal simulations*** based on: 1) BodyParts3D [16] surface-based atlas and SimTk-OpenSim [17] simulation platform (fig. 6b), multi-Surface Simplex (fig 2).
- Plans for ***DBS simulation*** via tractography-aware tet meshing and TheVirtualBrain [18].
- Extension of 1-Simplex via tree-space analysis include ***peripheral nervous system atlas***.
- ***Multiscale modeling*** feasible via ***multiresolution meshing*** and ***multigrid solvers*** [20].



(a) (b) (c) (d)

Figure 6. Future work. Therapy and function models for medical simulation (a) SOFA-based cutting [15]. (b) Musculo-skeletal simulation: top left: BodyParts3D; inset bottom right: SimTk-OpenSim. (c) Components of planned tract-aware DBS simulation (top to bottom): tractography and connectome; tract-aware meshing; TheVirtualBrain large-scale neuroactivation simulation. (d) PNS modeling plans: combination of 1-Simplex with Tree-space analysis (bottom).

4. Conclusions

- Overview of on-going work with emphasis on anatomical and functional modeling for neuro- and orthopedic surgery simulation and planning, and musculoskeletal dynamics.
- Numerous applications relevant to biomechanics, neuroscience, multiscale modeling.

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