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Approach-specific multi-grid anatomical modeling for neurosurgery simulation with public-domain and open-source software

Michel A. Audette^{a,1}, Denis Rivière^b, Charles Law^a, Luis Ibanez^a, Stephen R Aylward^a, Julien Finet^a, Xunlei Wu^c, and Matthew G. Ewend^d

^aKitware, Inc., 28 Corporate Drive, Clifton Park, NY 12065 USA

^bNeuroSpin, Bâtiment 145, Point Courrier 156, F91191 Gif-sur-Yvette Cedex, France

^cRENCI, Duke University, 390 Science Drive Extension, Durham NC, 27708, USA

^dDept. Neurosurgery, Univ. of North Carolina, 170 Manning Dr, Chapel Hill, NC, 27599, USA

Abstract

We present on-going work on multi-resolution sulcal-separable meshing for approach-specific neurosurgery simulation, in conjunction multi-grid and Total Lagrangian Explicit Dynamics finite elements. Conflicting requirements of interactive nonlinear finite elements and small structures lead to a multi-grid framework. Implications for meshing are explicit control over resolution, and prior knowledge of the intended neurosurgical approach and intended path. This information is used to define a subvolume of clinical interest, within some distance of the path and the target pathology. Restricted to this subvolume are a tetrahedralization of finer resolution, the representation of critical tissues, and sulcal separability constraint for all mesh levels.

Keywords

surgical simulation; neurosurgical approach; nonlinear biomechanics; meshing

1. INTRODUCTION

In clinical areas unrelated to neurosurgery, surgery simulation has made significant inroads in improving surgical skill and patient outcome. Double-blind validation studies have indicated that surgical residents who had trained with a simulator systematically outperformed residents without such training in performing laparoscopic cholecystectomies(1). The former also had a statistically better patient outcome(2). Meanwhile, a recent movement to limit resident duty hours (3), has resulted in compressed neurosurgical internship schedules (4). According to Grady et al., this situation entails “risks for public health associated with an inexperienced neurosurgical work force”(5).

¹corresponding author: michel.audette@kitware.com; www.kitware.com.

Despite the demonstrated advantage of simulation-based training over the traditional framework, whereby residents observe senior surgeons and gradually assume increased responsibility, simulation has made few inroads in neurosurgery. This limited impact can in part be ascribed to relatively inexpressive modeling of the anatomy.

This paper describes on-going work that will address some of the shortcomings of existing methods for neurosurgery simulation, and particularly in relation to the requirements of skull base surgery simulation, as illustrated by figure 1. As can be seen in this figure, one of the techniques available to the neurosurgeon for resecting deep-seated lesions in the skull base involves parting the brain tissue about the sylvian fissure. This is particularly true of the pterional approach (also known as frontotemporosphenoidal approach), which consists of approaching the brain and the anterior skull base through their lateral aspect by removing the frontal and temporal bones and the greater wing of the sphenoid (6). As suggested by Wen et al (7), the depth of the anterior part of the brain with its neural and vascular components can be considered as treasures located along a hallway and locked up behind a door: The door is the bony structures on the lateral surface of the skull; the sylvian fissure is the hallway; and the pterional approach can be considered as the key to the door... The extensive spectrum of the neural and the vascular structures within the reach of the pterional approach includes insula, basal ganglia, lateral ventricle, middle cerebral artery, temporal operculum, frontal and parietal opercula, uncus, orbit, anterior cranial fossa, optic nerve, internal carotid artery and branches, lamina terminalis, and interpeduncular fossa.

However, up to now, anatomical modeling for neurosurgery has emphasized brain models that can be characterized as monolithic, as well as relatively unexpressive in relation to critical tissues (8), which originally led to an emphasis on needle insertion in early prototypes (9)(10)(11).

Moreover, one of the main objectives of our work is to leverage innovations in nonlinear finite elements, in order to enable large deformations such as parting of brain tissue about a sulcus, which include the following.

- i. The application of precomputations based on the expression of finite elements in terms of undeformed coordinates, as in Total Lagrangian Explicit Dynamics (TLED) (12).
- ii. The recruitment of Graphical Processor Units in for accelerating the former technique (13).
- iii. The application of multi-grid finite elements (14), whereby a coarse mesh representation converges relatively quickly in response to a virtual surgical gesture and is then used to facilitate the convergence of finer-level representations, with coarse and fine meshes coinciding with the whole brain and a subvolume of clinical interest respectively.

The implications of these objectives related to biomechanics entail that the meshing should be controllable in terms of the size of each edge, to produce a coarse and fine meshes on the one hand, and where the size of the coarse-level matrix system should be limited to a few thousand nodes, and to control the size of the smallest edge that impacts the time-step of the

TLED formulation. At the fine level, the finite element formulation need not be TLED, so as to enable us to not be limited by small time-steps: promising alternate options include (15).

It should be emphasized that these biomechanics engines apply to surgical gestures where tissue is not cut or resected, but merely manipulated (the topology of the mesh does not change), such as the use of the spatula suggested in figure 1, by way of a 6 degree-of-freedom haptic device, or a clamp closing shut a blood vessel, by way of a 7 d.o.f. haptic device. The MPB Freedom 7S (16), illustrated in figure 2, affords both 6 and 7 d.o.f. configurations, both in terms of positioning and force feedback, a requirement for multi-tool interaction. Cutting models will be addressed in a future phase, possibly through the Extended Finite Element Method (17).

2. MATERIALS AND METHODS

2.1 Automatic sulcal labeling: BrainVISA and sulcus-aware morphological filtering

The first stage of our current processing method to produce descriptive anatomical models of the brain is the image analysis pipeline that segments T1-weighted MR data according to white and grey matter as well as corticospinal fluid, based on scale-space analysis (18), which is also the first step of the BrainVISA (19) public-domain image analysis pipeline. An alternate approach that to segmentation that is also open-source is the Expectation Maximization (20) segmentation available in the Slicer (21) platform. With both methods, a separate tumor modeling (22) will be required for practical patient-specific neurosurgery simulation.

This preliminary classification is followed by morphological analysis to separate hemispheres and detect sulci on the basis of a white matter skeleton, which are subsequently expressed as nodes within relational graphs, which nodes coincide with simple surface primitives of various topological types, as described in (23). The last computational stage of BrainVISA inputs this relational graph, within which each node is labeled according to its underlying surface type, to a multi-layer perceptron, which can deal with topological variability of sulci across individuals. The method proposed in (24), which extends the former method through a probabilistic atlas of sulcal position and a Bayesian approach to sulcal labeling, was found to work more robustly with our data, and is used here.

The output of the sulcal labeling pipeline is shown in figure 3, in the Results section, and is postprocessed to produce a suite of VTKPolydata files (.vtk file format), which serves as input to the next stage, in addition to the brain tissue segmentation produced in the preprocessing.

2.2 Tissue modeling based on surface meshing

The objective of the second stage is to produce a triangular surface mesh of the brain that is separable about one sulcus, such as the left Sylvian fissure for a pterional approach simulation on the left side of the patient's head. This mesh computation uses as input the data produced by sulcal labeling stage, namely a list of all sulci, as well as a tissue map: GM, WM, CSF, and pathology where applicable. Moreover, the surface mesh produced for modeling the brain must provide good control over resolution, i.e. produce no small edges,

since the time step of the TLED finite elements to be used in the simulation is proportional to the smallest edge length.

Prior to the computation of triangular surface mesh, the sulci are used to orient the morphological filtering of the binary brain volume, so as to prevent clinically irrelevant sulci from appearing in the anatomical model, while also imposing separability where the clinically relevant sulcus appears, namely the left Sylvian fissure. This stage is implemented with a series of morphological operations on each hemisphere:

- i. a small morphological dilation of a voxel-based representation of all sulci;
- ii. a small morphological closing of the brain binary OR'ed with the dilated irrelevant sulci;
- iii. a small morphological opening of the closed brain binary volume from step ii on the basis of the clinically relevant sulcus;
- iv. a blurring with a small kernel to produce brain hemispheres and subcortical structures from which stable results can be obtained by the application of Marching Cubes;
- v. a MAX operation of the blurred hemispheres and subcortical structure.

The justification for proceeding in this manner, rather than simply a closing of the brain binary volume with a large structuring element, is to preserve as much of the relevant detail, specifically the inter-hemispheric space and the ventricles, as possible, while simplifying the rest of the volume to enable representation by as elements that are as few and as coarse as possible in the less relevant portions of the brain.

The surface meshing stage proper currently consists of the following steps, as shown in figure 5.

- i. Marching Cubes-based triangular isosurface extraction, using VTK(25), from the result of step v) of the sulcal-labeling postprocessing above.
- ii. Repair of MC result with open-source MeshFix (26), to eliminate self-intersections.
- iii. Computational Geometry Algorithms Library (27)'s Triangulated Surface Mesh Simplification function, also known as `edge_collapse()`, which produces a mesh with few small edges and with good agreement with the original MC boundary. This decimation produces the surface that will serve as input to the tetrahedralization, compatible with finite elements (fairly constant edge lengths), while VTK's decimation methods generally provide results that are optimized for visualization of static scenes and are used here to produce a relatively sparse visual model for SOFA(28).
- iv. Finalization of the surface mesh decimation with the first author's simplex mesh code (29). We use the T1 and T2 operators to produce a dual simplex mesh that typically has 6-edge faces, which then produces triangular faces by duality that are near-equilateral. This process is illustrated in figure 5.

In conjunction with this development, we are also adapting open-source visualization to enable us to establish a subvolume of clinical interest based on distances to a linearized path, as shown in figure 6, based on Paraview (30). On-going work will expand on this notion of distance, to encapsulate a subvolume close to the boundary of the pathology as well as encapsulating a sulcus selected by the user, in conjunction with the approach chosen by the surgeon. Moreover, the mesh scale chosen for this subvolume will be smaller than that chosen for the brain volume, and we will use a multi-resolution representation in conjunction with multi-grid finite elements (14), which will be achieved over the next year.

Other applications of surface meshing relevant to this project include the following:

- i. The representation of a static surface mesh coinciding with the skin, muscles and skull, to synthesize a craniotomy, as shown in figure 7, based on MR data skull stripping available through Slicer. A Marching Cubes-based isosurface extraction is decimated here by `vtkQuadricDecimation` (25), to produce a high-quality static scene that is lightweight in terms of polygon count.
- ii. Blood vessels have been identified on the basis of a multi-scale Hessian-based operator (31) applied to MR angiography data of the same subject considered so far, as illustrated in figure 8, and represented with a dense mesh obtained by Marching Cubes. The post-processing that will be used with this mesh is the combination of the CGAL- and simplex-based decimation techniques described above, given the requirement that vessels also must be accounted for in our finite-element based simulation.

2.3 Tetrahedralization

The last stage to represent the brain is a tetrahedralization that affords good quality elements as well as good control over mesh size. Preliminary results were obtained using TetGen(32), and appear in figure 8. Comparison with other open-source tetrahedralization methods, including the Almost-regular Tetrahedralization (33) adopted in the past by the first author, is under way. TetGen generally preserves the mesh density properties of the surface mesh, while ART explicitly controls the mesh density through its edge length objective function.

3. RESULTS

Results of sulcal labeling for our subject data, made available from the repository used in (34) appear in figure 3. Figure 4 illustrates the result of the postprocessing of the sulcal labeling results, prior to the blurring stage: only the left Sylvian fissure and the ventricles are preserved. However, this stage currently does not account for blood vessels present in the brain, many of which are imbedded in this binary tissue.

Surface mesh results, which demonstrate some of the components of the decimation appear in figure 5. Further adaptations to the simplex model, to enable a sparser surface that is still faithful to tissue boundaries, is currently on-going.

Preliminary results of subvolume definition via Paraview appear in figure 6. A more integrated approach to subvolume definition, through the consideration of the pathology and the relevant sulci, is still on-going.

The application of Slicer's skull stripping to craniotomy synthesis appears in figure 7. A more descriptive scene is feasible through the modeling of dura mater, which has not been addressed yet, and the use of SOFA classes to model surgical draping. This craniotomy reflects a pterional approach, and would be revised on the basis of a neurosurgeon's choice of approach in conjunction with the position of the pathology within the brain. The idea is to provide a simple Slicer-based interface for synthesizing this static scene in a manner that is neurosurgical approach-aware.

Figure 8 represents the vessel tree of the same subject considered so far, subject 4 of the Montreal Neurological Institute's patient data used for the computation of a suite of digital phantoms (34). It is likely that only a subset of this vessel tree will be required for practical neurosurgery simulation, since not all of these critical tissues are at risk during any given procedure. For further details on vessels at risk in the pterional approach, see (7).

Figure 9 represents preliminary results of a tetrahedral mesh that is separable at the left Sylvian fissure. Further refinements to the method and its application to SOFA-based simulation of tissue displacement are both underway.

4. CONCLUSIONS AND FUTURE WORK

This paper presented on-going work on anatomical modeling for patient-specific neurosurgery simulation, where the brain model emphasized separability about one or more sulci, as well as resolution control, and where much of the work was built on public-domain and open-source software.

The consideration of sulci is based on a preprocessing stage that features a robust sulcal labeling technique, for which future developments will emphasize its ability to deal with patient data with imbedded topologies, rather than healthy subjects. For the time being, BrainVISA handles these through explicit masks in the GM-WM-CSF tissue map, but in general, its robustness in the presence of tumors has not been well validated.

The capacity of our method to produce surface and tetrahedral meshes that are even sparser than those shown so far, while maintaining topological fidelity as well as proximity to the tissue boundary, is still on-going. When this refinement is complete, the same meshing methods will be applied to a denser meshing the subvolume of clinical interest, consistent with multi-grid finite elements.

Biomechanics will largely be SOFA-based, beginning with the currently available TetrahedralCorotational-FEMForceField (28), followed by the soon-to-be-released GPU-accelerated TLED FEM class(35).

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Figure 1.
Justification for sulcal separability in brain meshing: a spatula parts brain tissue about the right Sylvian fissure,

Figure 2.
Freedom 7S haptic interface in 6 (top) and 7 d.o.f. (bottom) configurations for multi-tool surgery simulation.

Figure 3.
BrainVISA sulcal labeling of left hemisphere, with left Sylvian fissure shown in navy blue.

Figure 4. Sulcus-aware morphological preprocessing: green- opening about Sylvian fissure and closing about irrelevant sulci (ventricles and inter-hemispheric fissure are preserved); orange- original binary brain volume prior to processing.

Figure 5.
Surface meshing: (a) Marching Cubes result (2×10^6 polygons); (b) decimated Simplex mesh; (c) final triangular surface (1097 polygons), with opacity reduced to display ventricles.

Figure 6.
Interactive identification of subvolume of interest near planned surgical path, via Paraview.

Figure 7. Synthesis of static craniotomy scene for pterional approach, using Slicer's skull stripping.

Figure 8. Blood vessel tree of MRA data of MNI subject 4, produced by Aylward's Hessian-based vessel identification (31), whose integration into our multi-resolution brain model is still on-going.

Figure 9. Tetgen tetrahedralization (3039 tets), with each tet shrunk 50% for the purpose of visualization.