Surface-constrained Volumetric Registration (SVReg)

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http://brainsuite.org/processing/svreg/
Motivation for Brain Image Registration

- Analysis of morphometric changes
  - Progression of disease
  - Brain development over time
  - Group differences
  - Lesions, tumors

- Functional studies
  - Intersubject comparisons of fMRI, MEG, etc.
  - Longitudinal studies of same subject over a period of time

- We use image registration for transferring labels from atlas to subject.

- Inter- and intra-subject **surface** and **volume** alignment tools are required to integrate neuro-anatomical and functional data.
What is Image Registration?

Mapping from point $x$ of template brain image $T$, to match to a point $y$ of target brain image $S$ by a transformation $y = h(x) = x + u(x)$
BrainSuite Processing Workflow

<table>
<thead>
<tr>
<th>MRI</th>
<th>skull stripping</th>
<th>bias field correction</th>
<th>tissue classification</th>
<th>cerebrum identification</th>
<th>topology correction</th>
<th>tesselation</th>
<th>pial surface generation</th>
</tr>
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<tbody>
<tr>
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<td>40s - 4 min</td>
<td>&lt;5 sec</td>
<td>&lt;20 sec</td>
<td>&lt;40 sec</td>
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Cortex is often represented as a high resolution triangulated mesh with ~ 700,000 triangles.

We used this triangulated mesh representation of the surface for performing signal processing and analysis.
Cortical Surface

Average surface area = 960 cm sq.
(~1900 cm sq. for two hemispheres)

Equivalent to two 13” pizzas!

Each cortical area ~ one 3 cm pepperoni!
BrainSuiteAtlas I

- Single subject atlas labeled at USC by expert neuroanatomist
- 26 sulcal curves per hemisphere
- 98 volumetric regions of interest (ROIs), $35^2 = 70$ cortical ROIs

BCI-DNI Atlas

- Single subject atlas labeled at USC by expert neuroanatomist
- High-resolution (0.5 mm $\times$ 0.5 mm $\times$ 0.8 mm) 3D MPRAGE, 3T scan
- 26 sulcal curves per hemisphere
- 95 volumetric regions of interest (ROIs), $33^2 = 66$ cortical ROIs
Cortical Surface Parameterization

Corpus callosum

Mapping

Flat-map color coded by curvature
Extensions to Automatic Registration Without Sulcal Curves

Input mid surface

Smoothed surfaces

Cumulative curvature computation for multiresolution representation

Elastic matching for atlas and subject flat maps

<table>
<thead>
<tr>
<th>atlas</th>
<th>subject</th>
<th>warped subject</th>
<th>color-coded labels</th>
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</table>

- Elastic matching for atlas and subject flat maps.
Curvature Weighting

- Color coded curvature variance is shown in the figure.
- Computed by aligning 100 brains. Inverse of curvature variance is used as a weighting on the curvature cost function.
Refinement of Labels and Sulci

Original labels plotted on a smoothened representation of a cortical surface.

Labels after geodesic curvature. Flow plotted on a smoothened representation of a cortical surface.

Animation of the geodesic curvature flow for sulcal refinement.
Extension to Volumetric Registration

- **Accurate Sulcal Alignment**
- **Accurate Subcortical Feature Alignment**
- **Intensity-based Alignment**

- **Surface registration**
- **Extrapolation to volume**
- **Volumetric intensity registration**

- Solves the difficult problem of surface/sulcal registration in 3D volume.

- Surface and Volume Registration (SVReg) method performs accurate alignment of both cortical surfaces as well as subcortical volumes.

Automated vs Manual Labeling
SVReg may work with brains with lesions or other abnormalities

* The results might show varying degree of accuracy depending on how severe the abnormality in the brain is
More Examples of Lesion Brains
Cortical Surface Registration Based on Manually Traced Sulcal Curves (future release)

- Delineation protocol includes 26 sulcal curves per hemisphere
- Can trace all 26 or a subset of these curves to use as constraints

Sulcal curve delineation protocol: http://neuroimage.usc.edu/CurveProtocol_STS.html
Sulcal-Constrained Registration
(future release)

| Fully automated | With sulcal curve protocol |
SVReg Program and Interface

- Inputs of SVReg
  - Surfaces and volumes generated by BrainSuite.

- Outputs of SVReg
  - Labeled inner, pial and mid cortical surfaces.
  - Labeled brain volume.
  - Map from subject to atlas.
  - Point-wise cortical thickness, on subject and mapped to atlas.
  - ROI-wise cortical thickness, curvature, cortical areas of ROIs, gray matter, white matter and CSF volumes.
  - Spreadsheet of statistics.
  - Sulcal curves transferred from atlas to subject.
IMPROVED SUBCORTICAL SEGMENTATION

Earlier version

New version
LABELING OF HIPPOCAMPUS AND AMYGDALA

- The surfaces are not reliable near hippocampus and amygdala and therefore these labels tend to be inaccurate.
- The new code ignores surface constraints near these structures and rely only on intensity to get more accurate labeling.

Earlier version

New version
CORTICAL THICKNESS USING PARTIAL TISSUE FRACTION ESTIMATES

Figure: Thickness estimation procedure. (a) Gray-matter fraction estimated using a partial volume model; (b) Temperature map obtained using the proposed ALE method; and (c) Thickness estimate using the ALE method shown on the estimated mid-cortical surface.
THICKNESS COMPUTATION METHOD

**Features**

- invariant to convolution by unit integral kernel
- Avg thickness is more consistent with literature
- Shows higher significance in population studies

**Mathematical Formulation**

\[
\frac{\partial \phi(x, y, z, t)}{\partial t} = \text{div} \left( \frac{1}{f(x, y, z)} \nabla \phi(x, y, z, t) \right)
\]

\[T(x, y, z) = f(x, y, z) \frac{1}{||\nabla \phi_{\infty}(x, y, z)||}
\]
The p-value map of significant left-to-right cortical thickness differences estimated using the three different methods (LD, LE, ALE).

Average cortical thickness map estimated using (row 1) histology (von Economo, 2009), (row 2) Anisotropic Laplace Equation (ALE), (row 3) Isotropic Laplace Equation (LE), and (row 4) Linked Distance (LD) methods.
Utilities for Data Processing

- Smoothing functions on surfaces.
- Group differences: ROI-wise and Point-wise.
- Inverting the volumetric map.
- Regenerating stats file after manual corrections to the label file.
- Labeling of surfaces and volumes based on manually drawn cortical ROIs.
- Computing surface and volume stats for arbitrary ROIs.
- Create a new atlas for using with SVReg.

http://neuroimage.usc.edu/neuro/Resources/BST_SVReg_Utilities
Bias Correction Tool

Allows manual correction of the bias field

http://neuroimage.usc.edu/neuro/Resources/bfc_correction_tool
THANKS!

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<tr>
<th>3D surface L2 alignment</th>
<th>flat mapping</th>
<th>curvature alignment</th>
<th>transfer of labels</th>
<th>boundary refinement</th>
<th>3D harmonic mapping</th>
<th>intensity registration</th>
<th>volumetric label transfer</th>
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References

