Multi-Structure Whole Brain Registration and Population Average

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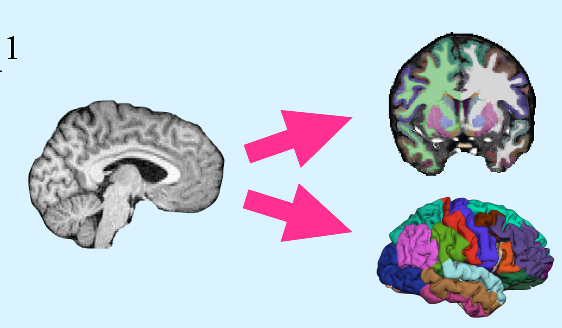
Introduction

- Inter-subject registration of whole brain MRI
  - Challenging: high anatomical variability, convoluted folding of the cortex
  - Many applications: morphometry, functional localization, atlas creation
- Feature-based
  - Uses lower dimensional representation of anatomy, but can possibly lack subtle information
- Intensity-based:
  - Uses anatomical image intensities to drive the registration, but lacks anatomical guidance
- Our approach uses segmented multiple structures of the brain as "features" to guide the MR-based registration

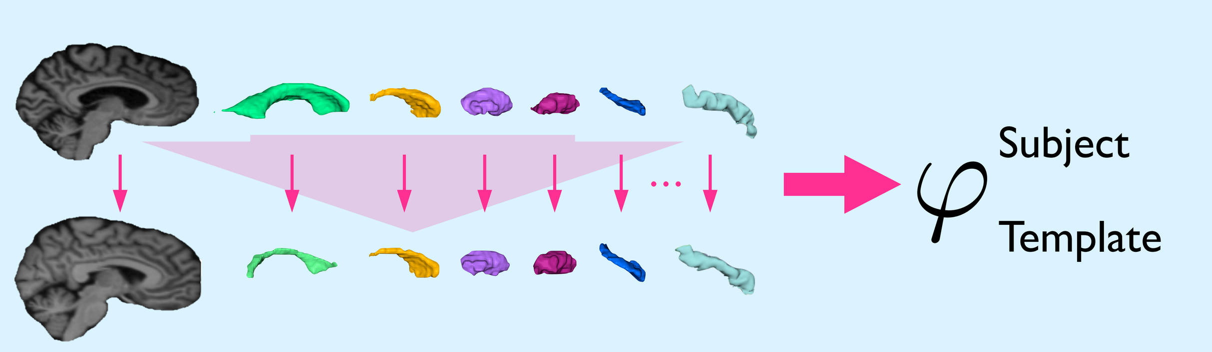
Initial Brain Segmentation

- Freesurfer image analysis suite
  - Subcortical segmentation[1]
  - Cortical surface reconstruction and parcellation[2]



Multi-Structure Registration

- Multiple simultaneous channels, each consisting of a different brain structure
- Diffeomorphic registration: 1-1, smooth, invertible
  - Large deformation diffeomorphic setting (LDDMM)[3]
  - Preserves topological properties of anatomy

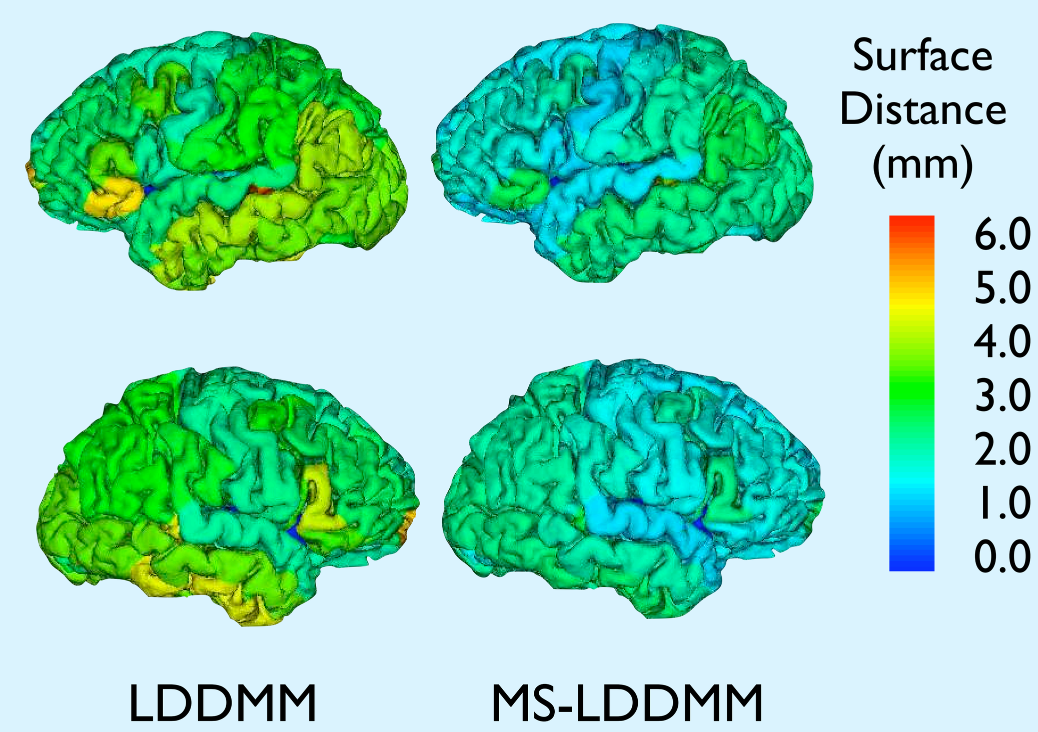


Results

- 1.5T brain MR scans brains from the Internet Brain Segmentation Repository (IBSR)[4]
  - Mapped all subjects to a chosen template
- Multi-structure LDDMM compared against:
  - Free-form Deformation B-splines, IRTK[5]
  - Single channel LDDMM
- Quantitative and qualitative evaluation

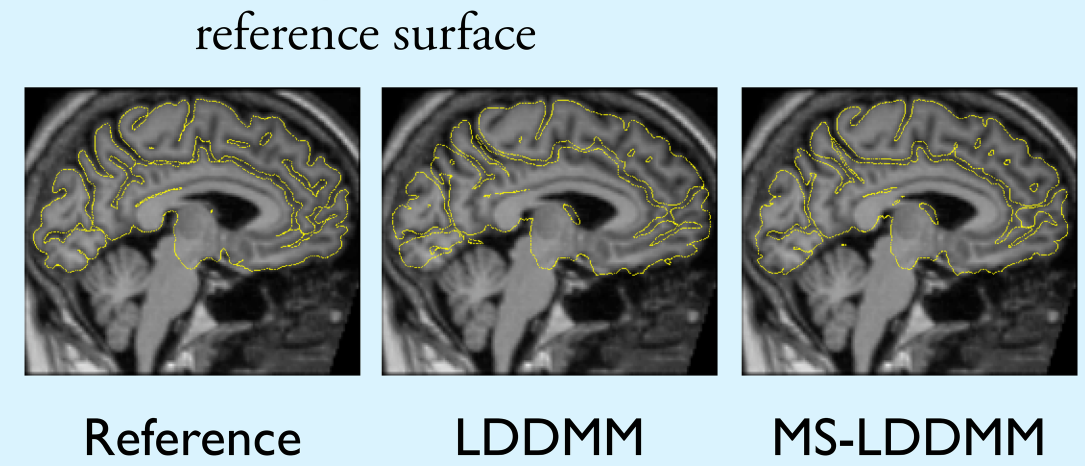
Cortical Surface Distance

- Mean surface distance between propagated and template surfaces



Cortical Surface Outline

- Qualitative visualization of the cortical surface alignment
  - Propagated cortical surface compared to reference surface



Cortical Surface Distance

- Overlap of propagated expert segmentations with the template: Dice similarity coefficient

$$DSC(A,B) = 2\frac{V(A\cap B)}{V(A)+V(B)}$$

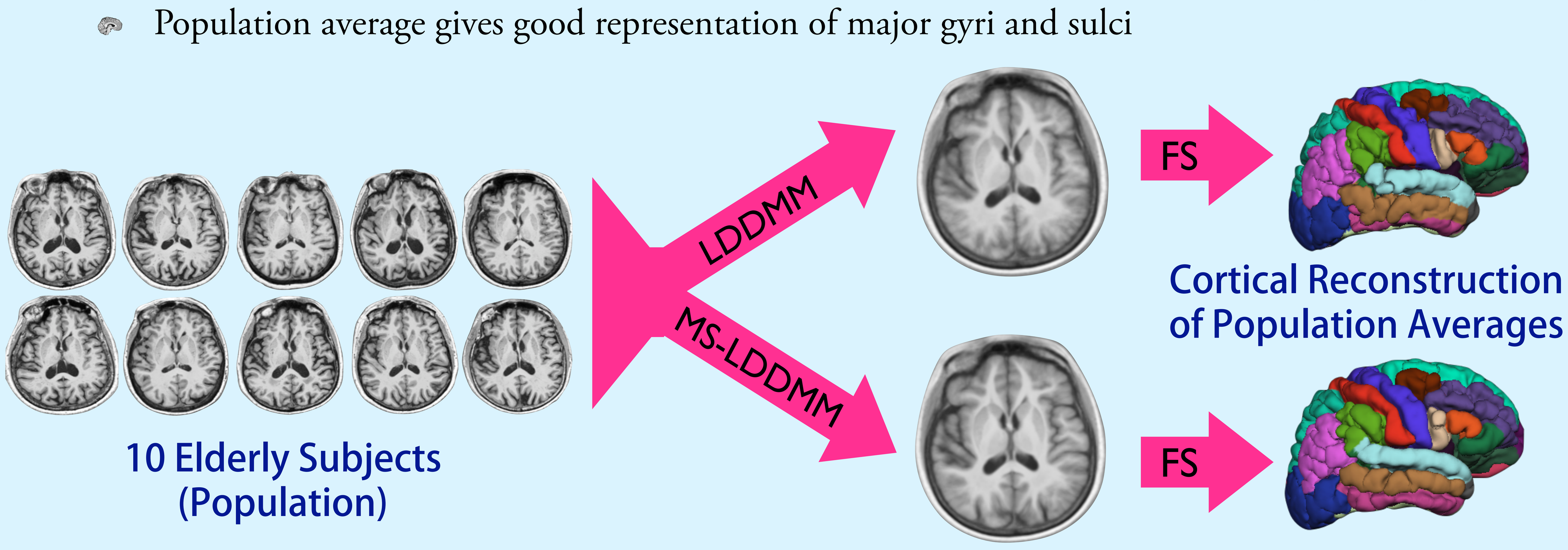
Structure	IRTK	LDDMM	MS-LDDMM
Lateral Ventricles	0.8	0.8	0.83
Thalamus	0.84	0.85	0.86
Caudate Nucleus	0.73	0.75	0.79
Putamen	0.76	0.8	0.81
Globus Pallidus	0.67	0.72	0.71
Hippocampus	0.65	0.65	0.73
Amygdala	0.54	0.57	0.66
Nucleus Accumbens	0.48	0.51	0.53
Frontal pole	0.62	0.61	0.66
Insula cortex	0.72	0.7	0.71
Frontal gyrus 1	0.51	0.55	0.63
Frontal gyrus 2	0.51	0.53	0.6
Frontal gyrus 3, pars triangularis	0.21	0.22	0.31
Frontal gyrus 3, pars opercularis	0.4	0.41	0.47
Precentral gyrus	0.51	0.52	0.61
Temporal pole	0.64	0.66	0.69
Sup. temporal gyrus, ant. division	0.38	0.41	0.46
Sup. temporal gyrus, post. division	0.49	0.45	0.6
Middle temporal gyrus, ant. division	0.38	0.39	0.43
Middle temporal gyrus, post. division	0.5	0.48	0.57
Middle temporal gyrus, temporo–occipital part	0.36	0.34	0.42
Inf. temporal gyrus, ant. division	0.33	0.35	0.38
Inf. temporal gyrus, post. division	0.42	0.44	0.49
Inf. temporal gyrus, temporo–occipital part	0.35	0.35	0.46
Postcentral gyrus	0.45	0.46	0.52
Sup. parietal lobule	0.38	0.39	0.46
Supramarginal gyrus, ant. division	0.39	0.4	0.48
Supramarginal gyrus, post. division	0.39	0.38	0.44
Angular gyrus	0.29	0.3	0.31
Lateral occipital cortex, sup. division	0.55	0.56	0.6
Lateral occipital cortex, inf. division	0.45	0.45	0.51
Intracalcarine cortex	0.42	0.42	0.56
Frontal medial cortex	0.51	0.46	0.51
Supplementary motor cortex	0.47	0.49	0.52
Subcallosal cortex	0.52	0.55	0.57
Paracingulate gyrus	0.53	0.51	0.57
Cingulate gyrus, ant. division	0.61	0.59	0.67
Cingulate gyrus, post. division	0.57	0.55	0.6
Precuneus cortex	0.5	0.49	0.57
Cuneal cortex	0.3	0.3	0.37
Frontal orbital cortex	0.46	0.45	0.52
Parahippocampal gyrus, ant. division	0.39	0.43	0.47
Parahippocampal gyrus, post. division	0.44	0.44	0.5
Lingual gyrus	0.45	0.44	0.53
Temporal frontal cortex, ant. division	0.22	0.25	0.22
Temporal frontal cortex, post. division	0.44	0.46	0.53
Temporal occipital fusiform cortex	0.39	0.37	0.51
Occipital fusiform gyrus	0.29	0.28	0.31
Frontal operculum cortex	0.44	0.42	0.44
Central opercular cortex	0.52	0.49	0.55
Parietal operculum cortex	0.35	0.29	0.45
Planum polare	0.5	0.48	0.54
Heschls gyrus 1	0.45	0.41	0.52
Planum temporale	0.45	0.39	0.52
Supracalcarine cortex	0.26	0.26	0.36
Occipital pole	0.51	0.5	0.59

Population Average Construction

- Extended unbiased diffeomorphic atlas construction[6] to incorporate multi-structure registration

$$\{\bar{\varphi}_i, \bar{I}\} =_{\varphi_i\in\mathcal{G}, I\in\mathcal{I}} \sum_{j=1}^{M}\left(\int_0^1 \|v_t^j\|_V^2 + \lambda^{MR}\|I^{MR}\circ\varphi_i - I_j^{MR}\|_{L^2}^2 + \sum_{i=1}^{N}\lambda^{Seg,i}\|I^{Seg,i}\circ\phi_{1,0} - I_j^{Seg,i}\|_{L^2}^2\right)$$

- Performed Freesurfer cortical surface reconstruction on the resulting population averages images
  - Population average gives good representation of major gyri and sulci



Conclusions

- Explicitly incorporating penalty for mismatch of cortical and subcortical segmentations
  - Notable improvements in cortical and subcortical structures
  - More accurate volumetry, morphometry, or functional localization in brain mapping studies
- Multi-structure Population average
  - Exhibits major cortical features well enough for cortical reconstruction
  - Valuable tool for interpretation, visualization and processing of anatomical data
- Limitations:
  - High computational cost with LDDMM; requires high-performance computing machines
- Future work:
  - Incorporate additional features such as fractional anisotropy or functional data

References

[1] B. Fischl, et al., "Whole brain segmentation ..." Neuron, vol. 33 (3), pp. 341–55, 2002.
[2] Dale et al., "Cortical surface-based analysis ..." Neuroimage, vol. 9 (2), pp. 179-194, 1999.
[3] M. F. Beg, et al., "Computing large deformation metric mappings ..." IJCV, vol. 61 (2), pp. 139–57, 2005.
[4] Data was provided by the Center for Morphometric Analysis at MGH: http://www.cma.mgh.harvard.edu/ibsr/
[5] Rueckert et al., "Nonrigid registration using free-form deformations ..." IEEE TMI, vol. 18 (8), pp. 712–21, 1999.
[6] Joshi et al., "Unbiased diffeomorphic atlas construction ..." Neuroimage, vol. 23 Suppl 1 pp. S151-60, 2004.

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