Registration of Cortical Surfaces Using Sulcal Landmarks for Group Analysis of MEG Data

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Introduction

We present a method to register individual cortical surfaces to a surface-based brain atlas or canonical template using labelled sulcal curves as landmark constraints. To map one cortex smoothly onto another, we minimize a thin-plate spline energy defined on the surface by solving the associated partial differential equations (PDEs). By using covariant derivatives in solving these PDEs, we compute the bending energy with respect to the intrinsic geometry of the 3D surface rather than evaluating it in the flattened metric of the 2D parameter space. This covariant approach greatly reduces the confounding effects of the surface parameterization on the resulting registration.

Surface extraction and parameterization

We first extract a mask for the cortical surface from an MRI volume using the Brainsuite software [1]. The topology of the mask is corrected automatically using a graph-based approach and tessellated to produce a genus zero surface. We then use a *p*-harmonic functional minimization scheme [2] to map the each cortical hemisphere onto the unit square. The result is a bijective mapping between each hemisphere and the unit square in which the interhemispheric fissure is constrained to map to the boundary of the unit square. This allows us to calculate partial derivatives across the boundary and explicitly model continuity between the two cortical hemispheres.

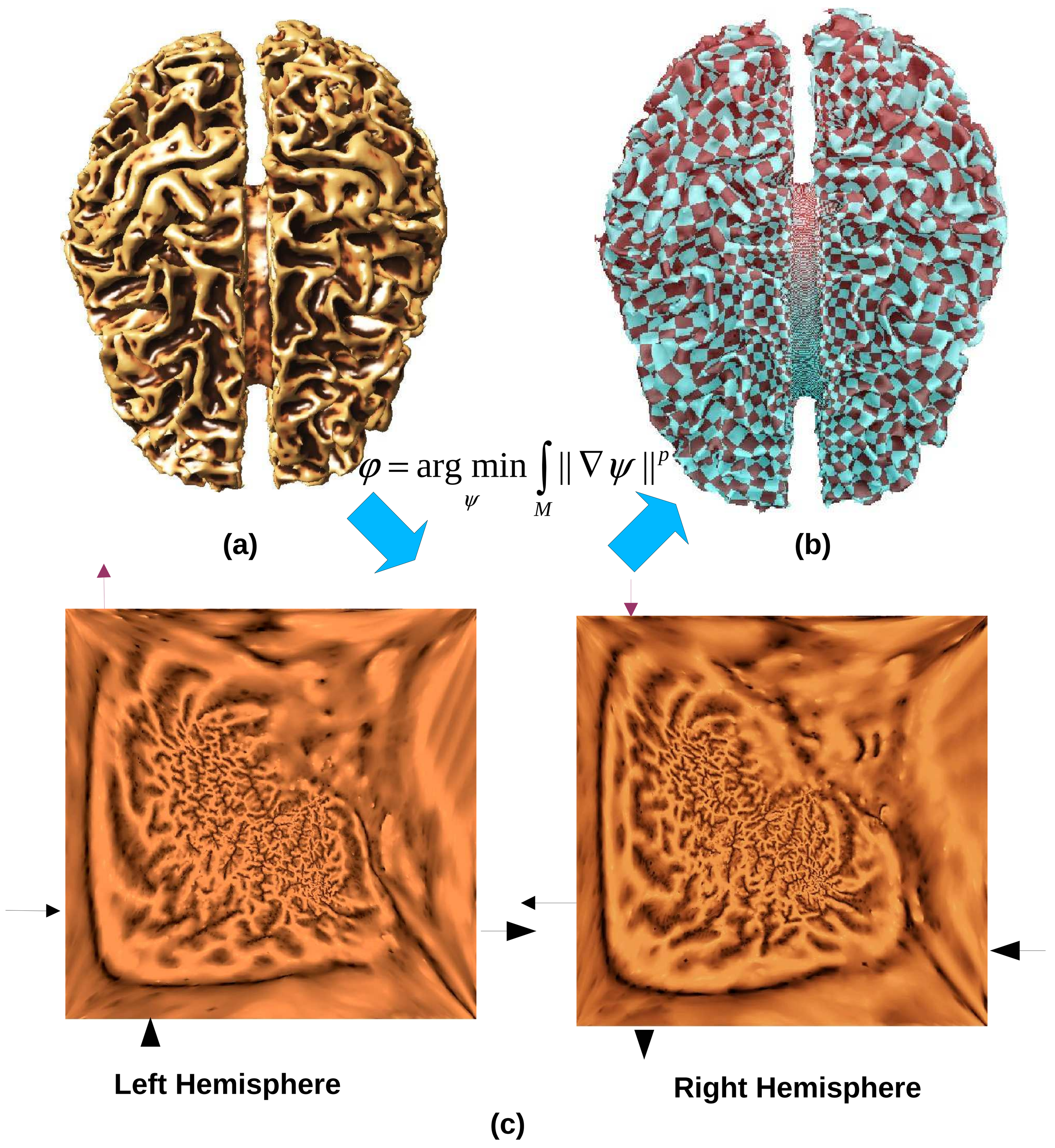

Figure 1: A cortical surface with hand labeled sulci; (b) A at map of the two cortical surface. The arrows show connectivity at points along the boundary of the square. Due to the spherical topology of the cortical surface, we can assign to it a coordinate system that allows us to compute partial derivatives across the interhemispheric ssure. (c) Chessboard texture mapped to the surface using the square maps.

$$E_b = \int \left(\frac{\partial^2\phi}{\partial x^2}\right)^2 + 2\left(\frac{\partial^2\phi}{\partial x \partial y}\right)^2 + \left(\frac{\partial^2\phi}{\partial y^2}\right)^2 dxdy$$

Thin Plate Bending Energy in Euclidean space

$$E_b = \int \left(\left(\psi^j{}_{,11}\right)^2 + \left(\sqrt{2}\psi^j{}_{,12}\right)^2 + \left(\psi^j{}_{,22}\right)^2 \right) g\, du\, dv$$

Bending Energy in non-Euclidean space

Calculations of covariant derivatives

$$g_{11} = \left\|\frac{\partial \mathbf{x}}{\partial u}\right\|^2, g_{22} = \left\|\frac{\partial \mathbf{x}}{\partial v}\right\|^2, g_{12} = \left\langle \frac{\partial \mathbf{x}}{\partial u}, \frac{\partial \mathbf{x}}{\partial v} \right\rangle^2, g = g_{11}g_{22} - (g_{12})^2$$

$$\phi^\beta{}_{,\sigma} = \frac{\partial \phi^\beta}{\partial u^\sigma} + \phi^\kappa \Gamma_{\kappa\sigma}{}^\beta \quad \text{where} \quad \sigma, \beta, \kappa \in \{1,2\}$$

$$\phi^\zeta{}_{,\beta\sigma} = \frac{\partial \phi^\zeta{}_{,\beta}}{\partial u^\sigma} - \phi^\zeta{}_{,\mu}\Gamma_{\beta\sigma}{}^\mu + \phi_\beta{}^\nu \Gamma_{\nu\sigma}{}^\zeta \quad \text{where} \quad \sigma, \beta, \zeta, \mu, \kappa \in \{1,2\}$$

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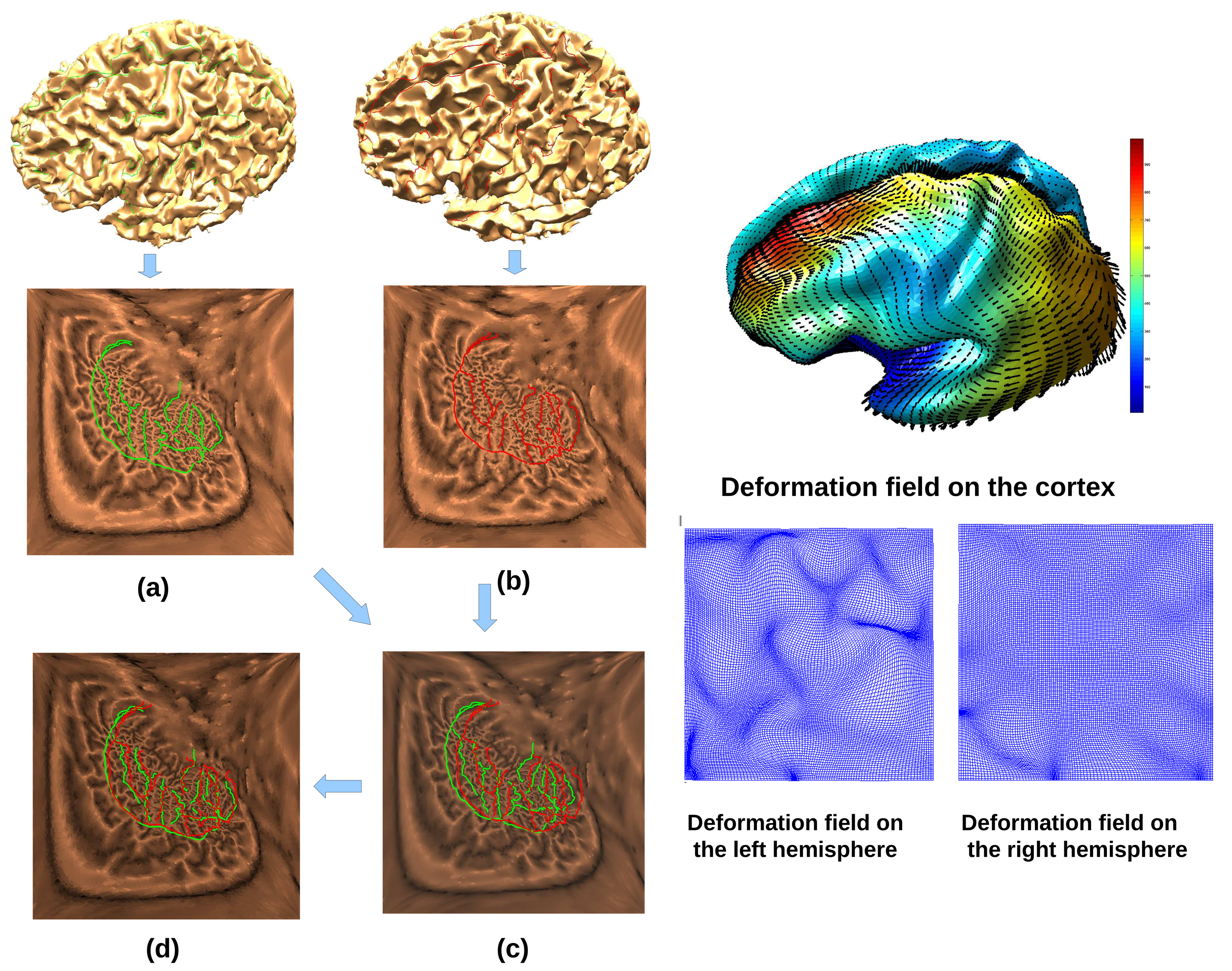

Figure 2: (a) A subject cortical surface with hand labeled sulci shown on the surface and in the at space; (b) a target cortical surface with hand labeled sulci shown on the surface and in the at space; (c) and (d) show sulcal alignment in the at parameter space before and after applying the covariant TPS deformation.

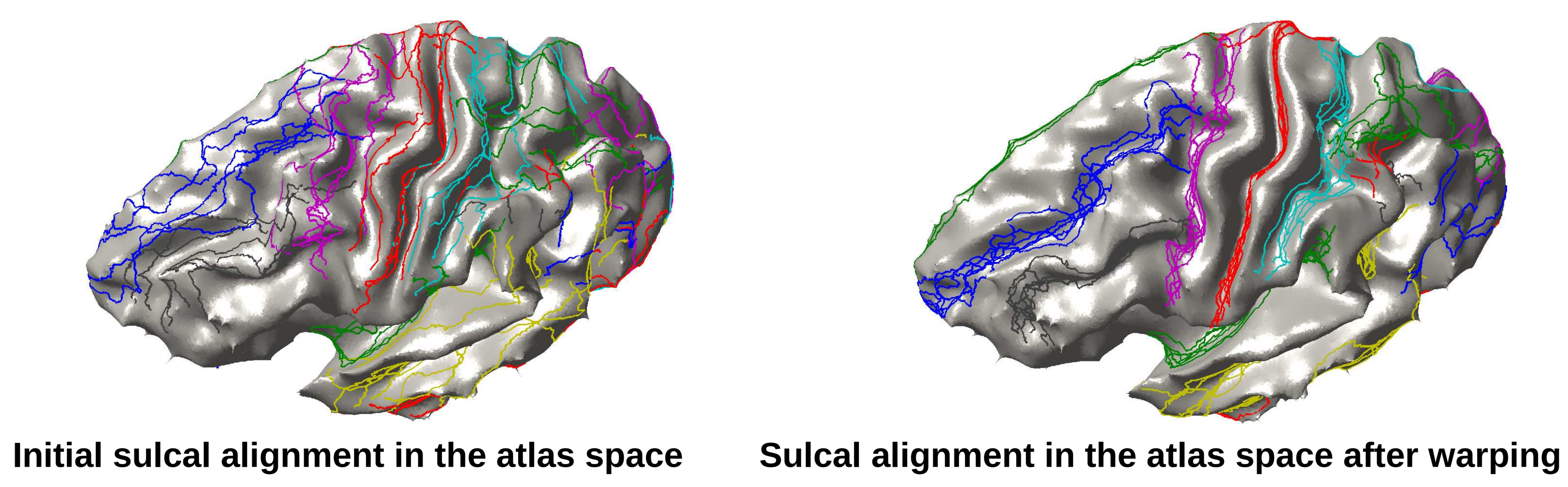

Figure 3: Alignment of the sulcal landmarks: 6 brains are registered to a common cortical surface using their p-harmonic maps in the plane. They are approximately aligned by the p-harmonic maps justifying our small deformation linear model (thin-plate bending energy model) which is used for landmark alignment.

TPS warping in the intrinsic geometry

Having parameterized the cortical surfaces of the subject and atlas, we align the coordinate systems between the subject and atlas such that a set of hand-labelled sulci are brought into register, i.e. we find a warping field which can be applied in the subject's surface parameter space to align the subject's sulcal features with those of the atlas. The alignment uses a set of interactively labelled sulci, sampled uniformly along their lengths, as a set of point constraints. To compute a smooth warping from one coordinate system to the other we use the thin-plate spline bending energy on the atlas surface as a regularizing function. Since the mapping onto the unit square will inevitably produce metric distortion relative to the original surface, it is attractive to compute the bending energy with respect to the intrinsic geometry of the 3D surface rather than the parameter space itself, using a *covariant* PDE approach [3]. To do this, we solve the biharmonic equation using covariant derivatives to obtain a thin-plate spline warp from subject to atlas coordinates.

Conclusions

Our metrically covariant method for nonlinear surface matching can help compare and integrate cortical data across subjects, by removing anatomical shape and sulcal patterning differences. By taking into account the surface metric in the registration process, covariant PDEs provide surface correspondences that are invariant to the particular parameterization of the surface, and the method to flatten it. This improves consistency and and may improve statistical power for group studies using cortically constrained maps of functional activation computed from MEG data.

References

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This work is supported by NIBIB under Grant No: R01 EB002010 and NCRR under Grant No: P41RR013642