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Diffeomorphic cortical registration under manifold sulcal constraints

Guillaume Auzias[a,e], Joan Alexis Glaunès[b], Arnaud Cachia[d,e], Pascal Cathier[d,e], Eric Bardinet[a,e], Olivier Colliot[a,e], Jean-François Mangin[d,e], Alain Trouvé[c], Sylvain Baillet[a,e]

[a]*Cognitive Neuroscience & Brain Imaging Laboratory, Pierre & Marie Curie University-Paris6, CNRS UPR 640–LENA, Hôpital de la Salpêtrière, France*
[b] *MAP5, Université Paris 5 - René Descartes, Paris, France*
[c]*CMLA, ENS de Cachan, Cachan, France*
[d]*NeuroSpin, CEA, Orsay, France.*
[e] *Federative Institute for Neuroimaging, IFR49*

Correspondence: G Auzias, Laboratoire de Neurosciences Cognitives & Imagerie Cérébrale CNRS UPR640 – LENA,47 boul. de l'hôpital 75651 Paris Cedex 13, France. E-mail: guillaume.auzias@chups.jussieu.fr, phone +33 1 42 16 14 03

Abstract. Brain mapping group investigation require spatial normalization across individuals. Here, we suggest to combine the benefits from 2 technical achievements to address this issue. First, the entire sulcal imprints of cortical surfaces are automatically extacted and simplified from T1-weighted MRI. Secondly, this sulcal information is introduced as measure-based landmarks into recent deformation techniques based on diffeomorphic tranformations. These transforms are readily applied to the entire cortical surface and naturally extend to the entire corresponding MRI volumes. We suggest that this type of approach is a significant alternative to purely image-based registration techniques.

Keywords: Diffeomorphisms; Registration; Sulcus; Manifold; Automatic; Deformation.

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1. Introduction

The problem of inter-individual brain co-registration has been approached through a considerable number of techniques. Because of substantial variability of the brain in shape and size across individuals, this problem may still be considered as ill-posed and the specific objectives of registration have many faces: e.g. from better detection of functional activations to elaboration of robust computational neuroanatomy indices. Recently, some groups have suggested considering co-registration as a surface-matching problem based on geometric features of the cortical manifold such as sulcal shapes [Collins et al., 1998; Vaillant and Davatzikos, 1999]. Effectiveness of geometric matching is questioned by 1) the robust and automatic extraction of cortical landmarks; 2) how a surface-based transform would extend to the entire brain volume. We suggest combining the benefits from two recent technical achievements to address these issues.

2. Material and Methods

Sulci are initially extracted from T1-weighted MRI and identified using the brainVISA free software platform (http://brainvisa.info) [Rivière et al., 2002]. Secondly, an automatic simplification procedure of each sulcal ribbon is applied. Finally, the resulting individual sulcal imprints are matched using recent registration techniques based on measure-valued landmarks supported by submanifolds via diffeomorphic measure transport [Glaunes et al., 2004].

2.1. Robust landmark extraction

The automatic extraction of landmarks may be obtained from an automatic process as available in the brainVISA platform. First, the intensity bias induced by MR data acquisition is corrected. Image segmentation of gray/white matter/CSF is achieved by analysing the intensity distribution of the MRI data and using mathematical morphology. Finally, elementary sulcal elements are segmented and divided into topologically simple surfaces which are eventually gathered into a graph structure.

Once sulci have been extracted, they are identified using pattern recognition techniques from a 90-sulcus label nomenclature. This step is completed for each of the elementary folds and relies on a neural network trained on a manually-labelled set. Decisions of the neural network consider both intrinsic and relational sulcal information. Correct recognition rate reaches 75% on average. Indeed, wrong labelling – or rather, disagreement between the computer and Human expert – is larger for cortical folds which variability is high across individuals. Labelling errors drop to less than 4% for e.g. the central sulcus, which reaches even better scores than the average disagreement between human experts.

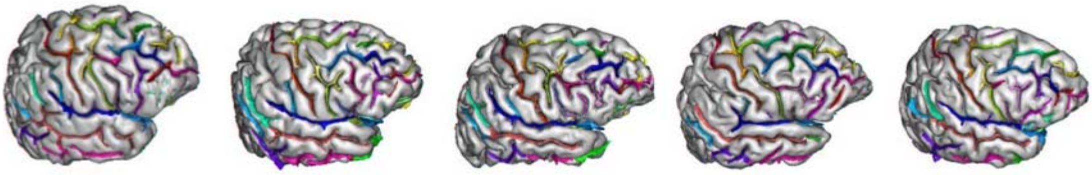

Figure 1. *Cortical surfaces and sulci as extracted from individual T1-weighted MRI in 5 adult subjects. Sulci are shown as coloured ribbons according to a predefined nomenclature.*

In this study, a simplified nomenclature of 70 sulci was used to avoid the largest labelling errors in areas of strongest interindividual variability. However, this non parametric landmark extraction leads to sulcal objects of very complex topology, which may impede subsequent efficient registration across a group of subjects. We therefore suggest simplifying these elemental building blocks to registration in the following principled manner.

2.2. Robust landmark simplification

The characteristic geometrical features of each sulcus are first extracted by keeping only the sulcal root (i.e. the fundus of each sulcus) and cortical superficial edges as exemplified on Fig. 2.

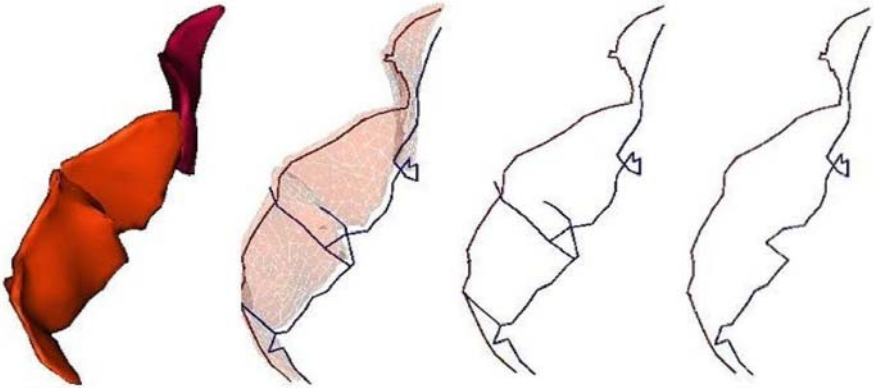

Figure 2. *Sulcal fundus and superficial edge of the right central sulcus (left, in red) are extracted and simplified. Each sulcus may therefore be summarized by these 2 simple but meaningful lines (right).*

Using a graph theory approach, each of these sulcal edges is decomposed in elementary line components by first detecting the singular points of these 3-D discrete curves as in Fig 3 (a-d). The secondary branches of the sulcal lines are then identified and removed using a longest-path approach, see Fig. 3 (e-f).

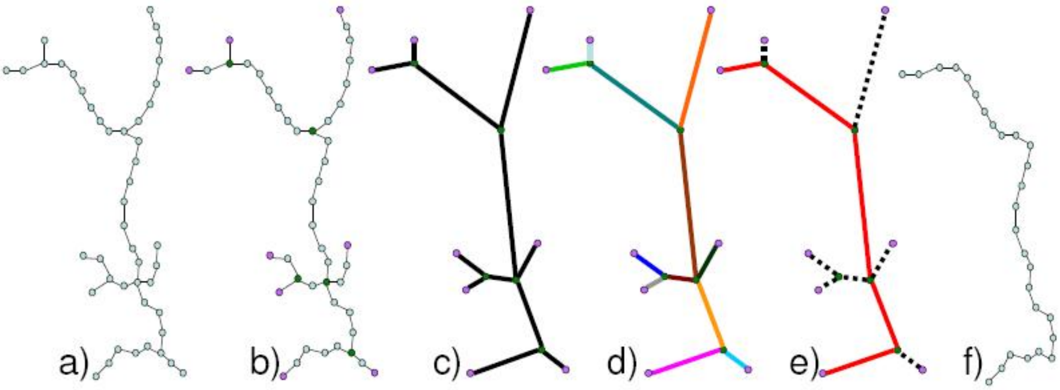

Figure 3. *Each root and superficial edges of every sulcus are automaticaly extracted and simplified.. The original complex object in a) is reduced to a simple line as in f) in a principled manner..*

This robust topological simplification is applied to every cortical sulcus and yields a uniformly-distributed set of essential folding features across the entire cortical surface as shown in Fig. 4 that will ultimately serve as landmarks to the co-registration procedure.

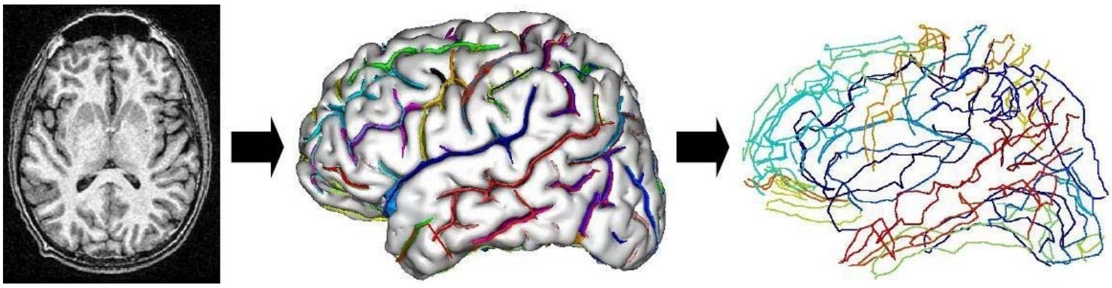

Figure 4. *Robust landmark extraction and simplification from T1-weighted MRI generate the individual sulcal fingerprint.*

These features define the individual sulcal fingerprint that will be matched across individuals as geometrical landmarks.

2.3. Measure Matching Algorithm

The optimal transformation that will co-register two individual brain surfaces is derived from the minimization of a cost function (Eq. 4) as a compromise between regularity of the deformation and fidelity to data [Glaunès et al., 2002].

Deformations ϕ are built by integrating time-dependent vector fields v_t, where $\phi = \phi_1^v$ is solution of the flow equation:

$$\partial_t \phi_t^v = v_t \circ \phi_t^v . \quad (1)$$

where $v_t \in \boldsymbol{V}$, the Hilbert space of regular vector fields, with specific assumptions.

In particular, V must be a reproducing kernel Hilbert space with kernel κ^V controlling the regularity of the final diffeomorphic transforms.
The energy of a deformation is defined as:

$$d^2(id, \phi) = \inf \left\{ \int_0^1 \|v_t\|_V^2 \middle| v \in L^2([0,1], V), \phi = \phi_1^v \right\} \quad (2)$$

The objects $(x_i) \subset \Re^3$ for landmark matching are modeled as a weighted sum of Dirac measures: $\sum_i a_i \delta_{x_i}$. The action of ϕ on every bounded and signed measure $\mu \in M_s$ is defined as the mass transportation, resulting here in:

$$\phi(\sum_i a_i \delta_{x_i}) = \sum_i a_i \delta_{\phi(x_i)} \quad (3)$$

and we also define I, a reproducing kernel Hilbert space such that $M_s \in \mathrm{I}^*$.

The measure-matching problem, with μ as a template and υ as target measures, is reduced to minimizing J in $L^2([0,1];V)$ with:

$$J(v) = \int_0^1 |v_t|_V^2 \, dt + \lambda \left| \phi_1^v . \mu - \upsilon \right|_{\mathrm{I}^*}^2 \quad (4)$$

The resulting deformation is a fully 3D diffeomorphic map defined everywhere in the MRI volume and obviously on the cortical surface.

3. Results

For evaluation purposes, the diffeomorphic co-registration transform was applied from each of the 5 subjects of Fig. 1 to a template, with the constraint that each sulcus landmark would pair with the corresponding landmark of the template brain. Results in Fig. 5 show that the spatial dispersion of the folds was considerably reduced and became more specific to anatomical territories.

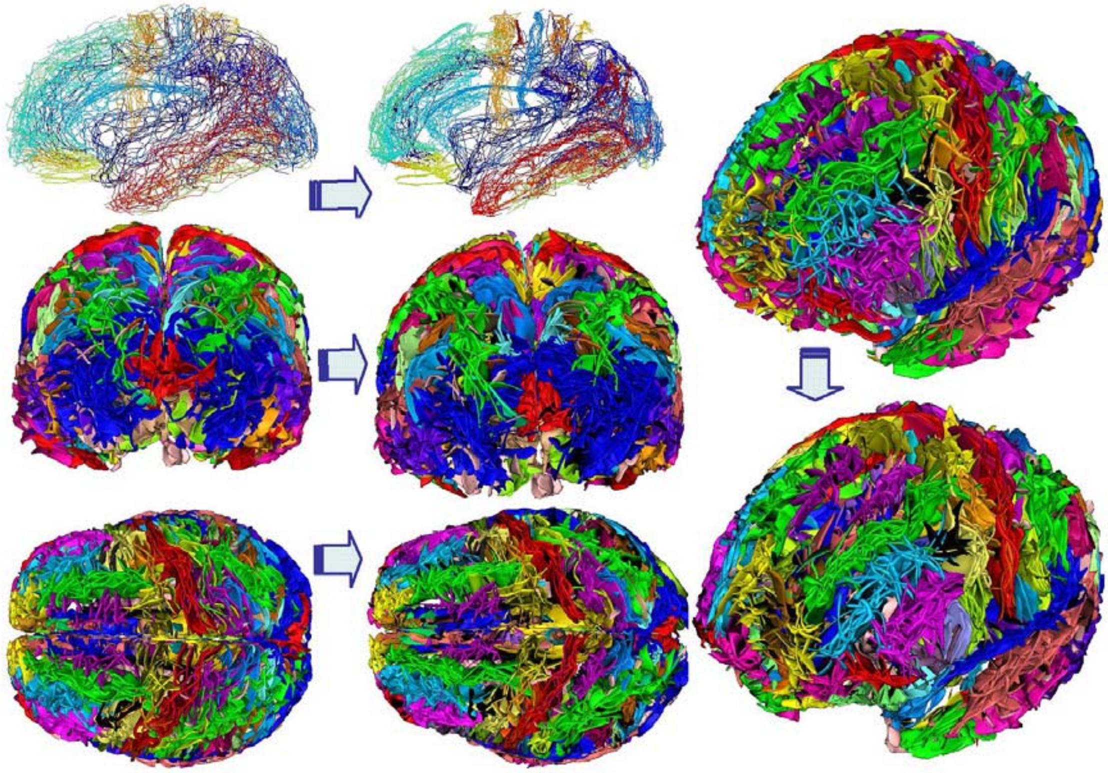

Figure 5. *Comparative results of the diffeomorphic registration compared to Talairach coregistration . Top row: overlay of sulcal fingerprint from 5 subjects after linear (left) and diffeomorphic (right) registration.Midle row : occipital view of superimposed sulcal folds as coloured ribbons before and after diffeomorphic registration. Bottom row: top view. Right coloumn : superio-frontal view. Sulcal alignment has considerably iimproved (see e.g.in the prefrotona lobe).*

4. Conclusions

The suggested approach combines the attractive properties of diffeormorphic matching with the pairing of anatomical landmarks usually considered by neuroanatomical experts. Results suggest this technique may lead to a new systematic approach for anatomical registration in several neuroimaging group studies.

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