QUASI-ISOMETRIC LENGTH PARAMETERIZATION OF CORTICAL SULCI: APPLICATION TO HANDEDNESS AND THE CENTRAL SULCUS MORPHOLOGY

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ABSTRACT

We present in this paper a method to perform a length parameterization of cortical sulcus meshes. Such parameterization allows morphological features to be localized in a normalized way along the length of the sulcus and can be used to perform population studies and group comparisons. Our method uses the second eigenfunction of the Laplace-Beltrami operator, and the resulting parameterization is quasi-isometric. The process is validated on the central sulci of a set of subjects and its efficiency is demonstrated by quantifying morphological differences between left and right-handed subjects.

Index Terms— cortical sulci, Laplace-Beltrami operator, mesh parameterization, morphometrics, handedness

1. INTRODUCTION

Cortical sulci are the main macroscopic landmarks on the surface of the brain. Although their relationship with functions is still a open and debated topic, it has been shown that their morphology can provide biomarkers of functional specificities such as handedness \cite{1,2}, or pathologies \cite{3}. Various measurements and representations of sulci have been used to study their morphology, such as sulcal lines \cite{4,5} or meshes\cite{1,2,6,7,8}.

In previous work we proposed a method to parameterize meshes representing cortical sulci \cite{1}. In particular this method provides a normalized localization along the length of the sulcus, which has been used for the localization of depth asymmetries of the central sulcus \cite{1,6} or the superior temporal sulcus \cite{9}, for the automatic detection and localization of the hand-knob \cite{7}, a morphological marker of the primary motor area of the hand \cite{10}, or for inter-species comparisons \cite{11}. Any point on the sulcus is localized with a value between 0 and 100 relative to its position between the dorsal and ventral extremities. Using such localization, sulcal shape descriptors such as depth curve \cite{1} and sulcal profile \cite{7} have been produced and used for group comparisons. This length parameterization relies on a two-step procedure: first the two extremities need to be detected on a mesh that describes the geometry of the sulcus; then this mesh is parameterized by means of a heat propagation process with the two extremities acting as sources. Problems with this approach \cite{1} are that: i) the algorithmic procedure to detect the extremities is costly and not entirely reliable (using geometric features such as curvature, and position and distance criteria); ii) the heat propagation process converge to a parametrization that is not isometric, and induces a higher density of coordinates towards the extremities. This is a problem since we use the coordinate for localization and depending on the position along the sulcus a small displacement could correspond to a larger change in coordinates.

In this paper we propose a method that solves both problems at once using the Fiedler vector, i.e. the second eigenfunction of the Laplace-Beltrami operator \cite{8}: extremities are detected using maxima of the Fiedler vector, which is a very fast and robust approach, and the initial parametrization induced by the Fiedler vector is then transformed to become quasi-isometric. After describing the method in section 2 we demonstrate its efficiency in section 3 by applying it to the left and right central sulci of left and right-handed subjects, and showing quantitative morphological differences between the two populations that had been previously reported qualitatively \cite{2}.

2. DATA AND METHODS

2.1. Data and preprocessing

We examined 34 healthy adult subjects, divided in two groups of 18 right-handed subjects and 16 left-handed subjects matched in age. High-resolution structural MRI was

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performed on the same 3T system (TRIO; Siemens, Erlangen, Germany) for each subject with a T1-weighted FLASH 3D sequence (TR=15 ms, TE=4.92 ms, flip angle 25°, 192 slices, slice thickness=1 mm, matrix: 256x256 mm). Each MR image was processed using the BrainVisa segmentation pipeline\(^1\) in order to produce segmentation of tissues, meshes of the pial and white matter, and a graph-based structural representation of all cortical sulci. The left and right central sulci were then manually selected in the graph, and meshes of the corresponding sulci was extracted (Fig. 1-a). Meshes were then length-parameterized as detailed below.

### 2.2. Quasi-isometric length parametrization of sulcal meshes

Let \( M \) be the smooth closed surface of a sulcus and \( \Delta_M \) the Laplace-Beltrami Operator (LBO) on \( M \). We denote \( \lambda_0 = 0 \leq \lambda_1 \leq ... \lambda_n \leq ... \) the eigenvalues of \( -\Delta_M \) and \( \phi_0, \phi_1, ..., \phi_n, ... \) an associated orthonormal basis of eigenfunctions in \( L^2(M) \) that satisfy:

\[
-\Delta_M \phi_n = \lambda_n \phi_n.
\]

For the spectral decomposition of the LBO on a discrete mesh, see [8]. The second eigenfunction \( \phi_1 \) of the LBO is called the Fiedler Vector. It has been noted that it describes the longitudinal extension of a shape, as stated in the revisited Hot Spot conjecture [12, 8]. In particular, we observed in [8] how the two points \( p_1 \) and \( p_2 \) on \( M \) that correspond to the minimum and the maximum values of the Fiedler vector are the two points which are the farthest to eachother on \( M \) with respect to the geodesic distance \( d_g \):

\[
d_g(p_1, p_2) = \max_{p, q \in M} d_g(p, q).
\]

Considering the extremely elongated shape of sulci (Fig. 1-a), it is intuitive that these two points would be the two extremities of the sulcus.

The Fiedler vector is a function that varies smoothly and increasingly between \( p_1 \) and \( p_2 \) (Fig. 1-b). We normalize this function such that it varies between 0 and 100, with 0 at the dorsal extremity and 100 at the ventral extremity of the sulci. For each integer value \( i \in [0; 100] \), we consider the isocontour \( c(i) \) of value \( i \), and compute its center of gravity \( M(i) \). By doing so, we obtain a discrete representation \( A_{M(i)} \) of the medial axis of the sulcus (Fig. 1-c). For each integer value \( i \), we compute the total length of the portion \( (A_{M(i)}(0), A_{M(i)}(i)) \) of the medial axis through the parameterization \( P_{iso}(A_{M(i)}) = \frac{100 * L(i)}{L_A} \). This parameterization is then sent back onto the entire mesh by means of a piecewise affine application:

\[
\forall v \in M, \text{ if } P_{iso}(v) = i \text{ then } L(v) = \frac{L_A(i+1) - L_A(i)}{L(i)}.
\]

\( \text{which results in a continuous quasi-isometric length parameterization of } M \) (Fig. 1-e).

### 2.3. Hand-knob position detection

Once the parameterization performed, the sulcal profile and the hand-knob markers \( L_1 \) and \( L_2 \) are extracted based on this parameterization, according to the procedure presented in [7]. The sulcal profile describes the shape of the sulcus along the dorsal-ventral axis. As presented in [7], it can be used to automatically detect the position of the hand-knob via the detection of two positional landmarks \( L_1 \) and \( L_2 \).

![Fig. 1](http://brainvisa.info)

**Fig. 1.** a) CS mesh; b) Fiedler vector and its two extrema; stripes indicate isocontours of the function; c) initial length parametrization \( P_{init} \); d) medial axis; e) quasi-isometric length parameterization \( P \); notice the regular spacing of the isocontours; f) resulting sulcal profile with the two hand-knob marker positions \( L_1 \) and \( L_2 \).

### 3. EXPERIMENTS AND RESULTS

The quasi-isometric parameterization was applied to all 34 subjects. A subset of 15 subjects was selected for validation of the algorithmic process. For these subjects, the heat-propagation parameterization process that was previously used in [1, 6, 9, 7] was applied to the left central sulcus, and both sulcus extremities were marked manually by an operator.

#### 3.1. Sulcus extremities

For each of the 15 sulci meshes, we computed the geodesic distance between the extremities detected by the min and max of the Fiedler vector and those that were marked manually. For the ventral extremity, the mean geodesic distance was 0.79mm, and for the dorsal extremity it was 0.73mm. Those results indicate that the average error across the 30 extremities...
is equivalent to the average distance between two neighboring vertices on a sulcus mesh, making the extremity detection extremely precise.

3.2. Isometric properties of the parameterization

In order to validate the quasi-isometric properties of the parametrization, the following procedure was applied to both parameterization process:

- On each of the 15 sulci, all iso-contours \( c(i) \) for parameter values \( i \) between 0 and 100 with a step of 4 \( (i = 0, 4, 8, \ldots) \) were extracted (Fig. 2).
- For each \( i \), the mean geodesic distance between \( c(i) \) and \( c(i + 4) \) was computed: \( \bar{d}_g(c(i), c(i + 4)) \) (Fig. 2).
- The standard deviation \( \sigma_d \) of \( \bar{d}_g \) was then computed over the entire sulcus in order to assess the regularity of the spacing between iso-contours, which is our measure of isometry (the lower \( \sigma_d \), the more isometric the length parameterization).
- \( \sigma_d \) was then averaged over the 15 sulci.

The results were as follow: for the heat-propagation parameterization, the average \( \sigma_d \) was 1.553; for our new method, the average \( \sigma_d \) was 0.266. This indicates the much better isometric nature of the parameterization. This is illustrated by Fig. 2 were the spacing between iso-contours is more regular for our parameterization than for the heat-propagation parameterization. The latter induces a higher density of coordinates towards the extremities and a lower one in the middle of the sulcus.

![Fig. 2. iso-contours of the length parameterization and computation of the mean geodesic distance between iso-contours. Left: heat-propagation parameterization. Right: quasi-isometric parametrization; notice the even spacing of iso-contours.](image)

3.3. Morphological differences between left-handed and right-handed subjects

The position of \( L_1 \) and \( L_2 \) in the parameter space (Fig. 1-f) was computed for all 34 subjects. As shown in [7], \( L_1 \) indicates the middle of the hand-knob (where the maximum curvature is reached), and \( L_2 \) indicates the ventral bound of the hand-knob (see Fig. 1-e). The average and standard deviation of both landmarks was computed across both groups of right- and left-handed subjects, for the left central sulcus and the right central sulcus. Results are presented in table 1 and plotted in Fig. 3.

### Table 1. Position of \( L_1 \) and \( L_2 \) for right (RH) and left-handed (LH) subjects.

<table>
<thead>
<tr>
<th>Group</th>
<th>Left CS</th>
<th>Right CS</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L_1(\sigma_{L_1}) )</td>
<td>( L_2(\sigma_{L_2}) )</td>
<td>( L_1(\sigma_{L_1}) )</td>
</tr>
<tr>
<td>RH</td>
<td>31.8(6.8)</td>
<td>42.7(9.6)</td>
</tr>
<tr>
<td>LH</td>
<td>39.1(2.8)</td>
<td>53.4(7.1)</td>
</tr>
</tbody>
</table>

These result show that on the left central sulcus the positions of \( L_1 \) and \( L_2 \) are significantly lower (more dorsal) for right-handed subjects than for left-handed subjects (Mann-Whitney, \( L_1: p = 0.0016, L_2: p = 0.0014 \)). On the right central sulcus, no significant difference was detected between the two groups. This shows that on the left central sulcus, the position of the hand-knob is more dorsal for right-handed subjects than for left-handed subjects, whereas on the right-central sulcus the position of the hand-knob is the same.

![Fig. 3. Position of \( L_1 \) and \( L_2 \) across both groups of subjects, and positional asymmetry of \( L_1 \) and \( L_2 \) between the left and right central sulci for both groups.](image)
Asymmetry of positions of $L_1$ and $L_2$ between the left and right central sulcus was also tested for each group (Fig. 3, bottom). For the right-handed subjects, we found that both the positions of $L_1$ and $L_2$ was significantly lower on the left central sulcus than on the right central sulcus (Mann-Whitney, $L_1$: $p = 0.0003$, $L_2$: $p = 0.0002$). For the left-handed subjects, no significant asymmetry was found. This shows that for right-handed subjects, the position of the hand-knob is more dorsal on the left central sulcus than on the right whereas for left-handed subjects there is no asymmetry. These results are extremely consistent with the findings that for right-handed subjects, the position of the hand-knob is located on average at $32\%$ of the sulcus length towards the dorsal extremity.

4. CONCLUSION

We presented a new method for the length parametrization of sulci, validated its ability to detect sulcus extremities and its quasi-isometric properties. We also demonstrated its efficiency by quantifying known morphological differences between left and right-handed populations. This method will be used in further studies to quantify sulcal morphological features such as depth or shape.

5. REFERENCES


