Automated Segmentation of Sulcal Regions

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Abstract. Automatic segmentation and identification of cortical sulci play an important role in the study of brain structure and function. In this work, a method is presented for the automatic segmentation of sulcal regions of cortex. Unlike previous methods that extract the sulcal spaces within the cortex, the proposed method extracts actual regions of the cortical surface that surround sulci. Sulcal regions are segmented from the medial surface as well as the lateral and inferior surfaces. The method first generates a depth map on the surface, computed by measuring the distance between the cortex and an outer “shrink-wrap” surface. Sulcal regions are then extracted using a hierarchical algorithm that alternates between thresholding and region growing operations. To visualize the buried regions of the segmented cortical surface, an efficient technique for mapping the surface to a sphere is proposed. Preliminary results are presented on the geometric analysis of sulcal regions for automated identification.

1 Introduction

With the advancement of magnetic resonance (MR) imaging techniques, high-resolution, high contrast three-dimensional images of the brain can now be routinely acquired in vivo. Techniques for modeling and automatically extracting information from such images have therefore emerged as a crucial component in furthering the understanding of brain structure and function. In particular, a topic that has recently received increased attention is the segmentation and identification of sulci [1,2,3,4,5,6]. Sulci identified on the cortex can then be used in applications such as localizing activation sites in functional imaging and deformable atlas registration algorithms. In addition, the geometric analysis of sulci will lead to a better understanding of normal versus diseased cortical geometry and the morphological changes that occur with disease.

Most previous work in the segmentation of sulci has focused on either fitting a surface [1,2,3] or finding a set of points [5] in between the sulcal banks. In this

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work, we present a method that segments the actual cortical regions surrounding sulci as opposed to extracting the sulcal spaces. The advantage of segmenting the actual surface is that a direct mapping of the cortical geometry is obtained. For ease of terminology, we refer to our segmented regions as “sulcal regions”, meaning precisely the buried regions of cortex surrounding the sulcal spaces. Another advantage of the proposed method is that it segments sulcal regions on the medial surface as well as the lateral and inferior surfaces. Also, this segmentation method is completely automated except for picking a seed point on the reconstructed cortical surface.

The segmentation is accomplished by reconstructing two surfaces for each hemisphere—the true cortical surface and an outer “shrink-wrap” surface. Sulcal regions on the true cortical surface are then segmented by their distance to the shrink-wrap surface. Because the sulcal regions are buried beneath the cortical folds, we briefly describe a fast method for generating a spherical representation of the cortical surface that facilitates their visualization. After the sulcal regions have been segmented, the next step is to anatomically identify each region as corresponding to a particular sulcus. We present some preliminary results on evaluating the characteristics of segmented sulcal regions that have potential for automatic sulcal identification.

2 Methods

Initial Data and Model Although our method is generally applicable to any reconstructed cortical surface [7,8,9,10,11,12], in this work, we use surfaces reconstructed from MR images generated by the technique described in [13]. This technique combines fuzzy segmentation, isosurfaces and deformable surface models to reconstruct the layer of cortex lying in the geometric center, which is approximately cytoarchitectonic layer 4. MR data was obtained from the Baltimore Longitudinal Study on Aging [14]. The reconstruction method is composed of three major steps. First, a three-class fuzzy segmentation of the MR data is computed corresponding to gray matter, white matter and cerebrospinal fluid. Second, an initialization for the deformable surface model is created by generating a smoothed isosurface from the white matter membership function obtained from the segmentation. The result of the isosurface algorithm is a mesh that is a discrete representation of the continuous isosurface. Finally, a deformable surface model is used to refine the initial surface to the central layer of the gray matter. The cortex reconstruction method requires a minimal amount of manual interaction and is capable of fully resolving deep convoluted folds.

To allow visualization of the buried sulcal regions, a spherical representation of the reconstructed cortical surface is generated that maintains a one-to-one mapping with the original reconstructed surface. This “spherical map” is generated by reducing the number of vertices in the cortical surface mesh to a few points and then rebuilding the mesh to a sphere in conjunction with a multi-resolution relaxation process. The mesh is reduced by a progressive mesh decimation originally described in [15] and subsequently in [16]. In a progressive

mesh decimation, a complex mesh is reduced to a simplified base mesh while storing the information necessary to rebuild the original mesh. In the spherical map generation, we first decimate the cortical surface mesh and then use the resulting base mesh and stored information to rebuild the mesh to a sphere. This is accomplished by initially projecting each vertex of the base mesh to a sphere. As each vertex is subsequently added back to the mesh, it is placed on the sphere while maintaining the correct neighbor topology. At various stages in the rebuilding process the vertices on the sphere are allowed to undergo elastic relaxation in order to avoid anomalous topologies. Compared to methods based purely on elastic deformations, this iterative rebuilding and multi-resolution smoothing process is typically six times faster, requiring only about one hour on an Silicon Graphics O2 R10000 workstation.

Segmentation. In this section, we describe the method for automatically segmenting the sulcal regions from a reconstructed cortical surface. The basic principle of the segmentation method is that regions of cortex that are not part of the outer, gyral surface are considered to lie in sulci. This outer surface, which we call a “shrink-wrap”, tightly surrounds the reconstructed cortical surface, but does not enter into the cortical folds. Sulcal regions are then defined based on distances between the cortical surface and the shrink-wrap surface. In order to segment the sulcal regions on the medial surfaces as well as the lateral and inferior surfaces, a shrink-wrap surface must be generated for each hemisphere separately. To this end, the reconstructed cortical surface is divided into two separate hemispheres by applying a cut through the corpus callosum. This step requires a user-defined seed point at the center of the corpus callosum, the only manual interaction required during the entire segmentation procedure.

The shrink-wrap surface is generated for each hemisphere using a deformable surface model. Focusing on one hemisphere, a deformable surface is initialized as an ellipsoidal mesh and allowed to deform to the outer cortical surface according to external and internal forces. The external forces drive the deformable surface model toward the cortical surface using standard gradient based potential forces [17] derived from an edge map. The edge map, shown in Fig. 1(a), is generated by discretizing one hemisphere of the reconstructed cortical surface. High internal forces are used to force the deformable surface to have a high tension, thus reducing its ability to enter into the cortical folds. The use of high internal forces, however, can sometimes cause the deformable surface to break through the gyri as shown in Fig. 1(b). To avoid this, an additional external force is introduced into the model. This force, which we call a barrier force, prevents the deformable surface from moving into parts of the image marked as barrier regions. A barrier region that prevents the deformable surface from shrinking into the gyri is created by applying a unidirectional inward dilation to the edge map. Additionally, the hole introduced at the corpus callosum is filled by adding points along the path originally used to introduce the cut. The resulting barrier region, shown in Fig. 1(c), allows for high tension on the deformable surface while preventing it from shrinking into the cortical surface. Fig. 1(d) is a coronal cross-section showing a contour of the final shrink-wrap surface in gray and the

reconstructed cortical surface in white. Parameter values required for the deformable surface algorithm were determined empirically from one data set and held fixed for subsequent data sets.

Fig. 1. Cross-sectional view of (a) the edge map generated from the cortical surface, (b) the deformable surface breaking through gyral regions, (c) the barrier region, and (d) the shrink-wrap surface superimposed on the cortical surface.

In the next step, the deep sulcal regions are discriminated from outer, gyral regions by computing the three-dimensional Euclidean distance from each vertex on the cortical surface to the nearest vertex on the corresponding shrink-wrap surface. Fig. 3(a)¹ shows a resulting depth map plotted on a lateral view of the spherical map, where larger depths are plotted in red and gray and smaller depths are plotted in blue. The corresponding lateral view of the convoluted cortical surface is shown in Fig. 3(b). This figure illustrates that buried sulcal regions can be identified by their greater distances to the outer shrink-wrap surface. For example, the largest gray region towards the bottom of the spherical map is the insular cortex and the vertical region above the insula with a slight posterior to anterior orientation is the cortical region surrounding the Central sulcus.

In order to obtain separate parametric surface segments for each sulcal region, points within a sulcal region must be connected. A simple approach would be to apply a single thresholding operation to the depth map, followed by a region growing algorithm that connects clustered regions to form sulcal segments. The shortcoming of this approach is that, because of the complex cortical geometry, there is no single threshold that can simultaneously extract the full extent of each sulcal region while preventing separate sulcal regions from joining together. This is because a high depth threshold segments only the deepest portions of a sulcal region, while a low depth threshold results in the joining of distinct sulcal regions. Thus, a hierarchical approach is applied that initially sets the threshold to a large value and relationships between regions are defined as the threshold is

¹ Figures are referenced out of order because color figures appear at end of text.

gradually decreased. This allows for sulci to be defined as distinct at the deeper regions of the cortex where they are believed to be more stable.

First, an initial sulcal segmentation map is computed from the depth map using a threshold of 10 pixels, where a pixel is .9375 millimeters. Vertices on the cortical surface with a depth greater than the initial threshold are considered to lie in sulcal regions. Clustered vertices are then joined to form parametric sulcal segments and each region is assigned a distinct but arbitrary numerical label. The resulting sulcal map, shown in Fig. 5(a) extracts the most buried portions of the deeper sulci. Next, the depth threshold is slightly decreased. Clustered vertices that have a depth between the previous threshold and the new threshold are joined to form new regions. These new regions are assigned numerical labels according to a set of rules designed to expand previously extracted regions while preventing separate regions from joining together. These rules are given as follows:

1. If a region is not adjacent to any previously labeled regions, it is assigned a new numerical label.
2. If a region is adjacent to a single previously labeled region, it is assigned the numerical label of the adjacent region.
3. If a region is adjacent to two or more previously labeled regions, it is labeled as a bridge region.
4. If a region is adjacent to a bridge, this region is also labeled as a bridge (this rule applies only to subsequent hierarchical levels).

After the region growing is complete, non-bridge regions with areas below a specified size are removed. This process is repeated for each thresholding level. Fig. 5 shows the sulcal map at various thresholding levels where the bridges are shown in black. This figure demonstrates how this hierarchical thresholding and region growing algorithm segments the full extent of the sulcal regions, but prevents separate sulcal regions from connecting together. After the final iteration of the above process, all bridges are relabeled as gyral regions.

3 Segmentation Results and Discussion

The sulcal segmentation method was applied to three reconstructed cortical surfaces with a typical result shown in Fig. 6. In each image of Fig. 6, the segmented regions are superimposed on either a translucent cortical reconstruction or its spherical map. Once segmented, each sulcal region can be manually identified as the region of cortex surrounding a specific sulcus. For example, on the right lateral surface are the regions corresponding to the Superior Temporal sulcus (green), Sylvian fissure (magenta) and Central sulcus (blue). On the medial surface, the Parieto-Occipital (orange), and Calcarine (purple) sulcal regions are segmented as well as the Cingulate sulcal region which is composed of several segments arcing from anterior to posterior. Sulcal regions segmented from the medial surface are also visible in the top view of the spherical map. Several other sulcal regions, such as the right Superior Frontal seen at the bottom left of

Figs. 6(b) and (e), are segmented as several pieces. The fragmented segmentation of sulci that are interrupted or pseudo-interrupted (meaning the interruption occurs within the sulcal fold [18]) has both advantages and disadvantages. The disadvantage is that fragmented regions need to be identified as belonging to a single sulcal region. The advantage is that these fragments can be used to quantitatively analyze the characteristics of interrupted sulci. Another complexity of cortical geometry is that two distinct sulci may be joined, meaning there is no gyral ridge separating them, even at the sulcal fundi. In this segmentation method, a single sulcal region will be extracted for two sulci that are joined.

Fig. 2. Region of cortex surrounding the Central sulcus segmented from six hemispheres.

The segmented regions corresponding to the Central sulcus from the six hemispheres are shown in Fig. 2. To aid in visualization, the side of the surface closer to the white matter is colored light gray, while the side closer to the cerebral spinal fluid is colored dark gray. This figure illustrates that although variability exists across subjects, these sulcal regions share some characteristic geometric features.

4 Geometric Analysis of Segmented Sulcal Regions

In this section, we investigate the potential for using geometric quantities computed for each sulcal region to automatically identify their anatomical designation. Three geometric features are computed for each segmented sulcal region and evaluated on the basis of whether the sulci might be distinguishable based on these features. The features used in this preliminary study are area, center of mass in Talairach coordinates and orientation.

For the area computation, the surface area in mm^2 is computed for each polygonal face in the region and these areas are summed. In order to compute the center of mass of each segment in Talairach coordinates, the surface is transformed into the standard three-dimensional Talairach space [19] and then computed as follows:

$$\mu = \frac{1}{N} \sum_{i=1}^N v_i \quad (1)$$

where N is the number of vertices in the extracted sulcal segment and v_i is the location of each vertex in three-dimensional space.

The orientation of each segmented region in the standard three-dimensional Talairach coordinate space is characterized by an orientation vector. This vector is computed by first computing the covariance matrix,

$$\Sigma = \frac{1}{N-1} \sum_{i=1}^N (v_i - \mu)(v_i - \mu)^T. \quad (2)$$

The eigenvector associated with the maximum eigenvalue of Σ yields the orientation of the segmented region. The eigenvectors are restricted to point in the positive Z direction guaranteeing uniqueness.

The surface areas computed for each segmented region of three cortical surfaces are shown in Fig. 4(a). The x -axis is the identification number of each segmented region and the y -axis is the surface area in mm^2 . The regions of cortex corresponding to the right and left Sylvian fissures are easily identified as having the two largest area measurements in each plot. Fig. 4(b) shows the Talairach centers of mass for a few selected sulcal regions from six hemispheres where regions corresponding to a particular sulcus are colored the same. The color scheme is as follows: Central sulcus (yellow), Sylvian fissure (green), Parieto-Occipital sulcus (blue) and Calcarine sulcus (red). In one of the hemispheres, the Parieto-Occipital and Calcarine sulci were connected resulting in a single segmented region corresponding to both sulci. This region is colored in cyan. This figure illustrates that the centers of mass for these sulcal regions in all six hemispheres cluster quite well in three-dimensional space, especially for regions corresponding to the Central sulcus and Sylvian fissure. Fig. 4(c) shows the orientation vectors computed for each segmented region from one cortical surface superimposed on the segments themselves. The origin of each orientation vector is the center of mass of its corresponding segment. This figure illustrates that the orientation vector describes the directionality of each segmented region. The orientation vectors of a few selected regions from six hemispheres are plotted in Fig. 4(d) with each vector centered at the origin. The color scheme used is the same as in Fig. 4(b). This plot illustrates the strong y orientation of the Calcarine sulcal region as opposed to the strong z orientation of the Parieto-Occipital sulcal region, indicating that this quantity could be used to discriminate these two regions that have similar locations in three-dimensional space. The three geometric quantities computed can be combined to form a high-dimensional geometric feature vector that characterizes the geometry of each segmented region. Used alone, these geometric features may not be sufficient to automatically identify sulcal regions. But from the results of our preliminary analysis, automatic identification may be possible when the various geometric features are combined.

5 Conclusions and Future Work

We have described an automated method that segments the full extent of sulcal regions while maintaining separate regions as distinct. Geometric quantities computed for each sulcal segment show promise for the automatic identification of their anatomic designation. We are currently working to apply our segmentation method and geometric analysis on additional data sets. This will allow us to test our hypothesis of automated labeling based on high-dimensional geometric feature vectors.

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Fig. 3. Computed depths displayed on a lateral view of (a) the spherical map and (b) the convoluted cortical surface.

Fig. 4. Geometrical features: (a) surface areas of all segmented sulcal regions from three cortical surfaces, (b) Talairach centers of mass of selected sulcal regions from three cortical surfaces, (c) orientation vectors of all segmented regions from one cortical surface and (d) orientation vectors of selected sulcal regions from three cortical surfaces.

Fig. 5. Sulcal map shown at a threshold of (a) 10 (b) 7 (c) 4 and (d) 2 pixels, where a pixel is .9375 mm.

Fig. 6. Resulting sulcal segmentation superimposed on (a) lateral (b) top and (c) medial views of the reconstructed cortical surface and (d) lateral and (e) top views of the spherical map.