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Automatic extraction of sulcal lines on cortical surfaces based on anisotropic geodesic distance

Joon-Kyung Seong [a], Kiho Im [b], Sang Wook Yoo [a], Sang Won Seo [c], Duk L. Na [c], Jong-Min Lee [b,]*

[a] Computer Science Department, KAIST, Korea
[b] Department of Biomedical Engineering, Hanyang University, Korea
[c] Department of Neurology, Sungkyunkwan University, Samsung Medical Center, 50 Ilwon-dong, Kangnam-ku, Seoul 135-710, South Korea

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ABSTRACT

Analyzing cortical sulci is important for studying cortical morphology and brain functions. Although sulcal lines on cortical surfaces can be defined in various ways, it is critical in a neuroimaging study to define a sulcal line along the valley of a cortical surface with a high curvature within a sulcus. To extract the sulcal lines automatically, we present a new geometric algorithm based on the computation of anisotropic skeletons of sulcal regions. Because anisotropic skeletons are highly adaptive to the anisotropic nature of the surface shape, the resulting sulcal lines lie accurately on the valleys of the sulcal areas. Our sulcal lines remain unchanged under local shape variabilities in different human brains. Through experiments, we show that the errors of the sulcal lines for both synthetic data and real cortical surfaces were nearly as constant as the function of random noise. By measuring the changes in sulcal shape in Alzheimer's disease (AD) patients, we further investigated the effectiveness of the accuracy of our sulcal lines using a large sample of MRI data. This study involved 70 normal controls (n [men/women]: 29/41, age [mean $\pm$ SD]: 71.7 $\pm$ 4.9 years), and 100 AD subjects (37/63, 72.3 $\pm$ 5.5). We observe significantly lower absolute average mean curvature and shallower sulcal depth in AD subjects, where the group difference becomes more significant if we measure the quantities along the sulcal lines rather than over the entire sulcal area. The most remarkable difference in the AD patients was the average sulcal depth (control: 11.70 and AD: 11.34).

Introduction

Analyzing the shapes of cortical surfaces is a key problem in neuroscience. For example, cortical sulci are important structures in brain registration (Hellier and Barillot, 2003), in discovering brain diseases and monitoring brain growth (Thompson et al., 2004), and in measuring brain variability (Fillard et al., 2007). Sulcal depth maps can also be used for guiding both surface- and volume-based brain warping algorithms (Kao et al., 2007; Thompson and Toga, 1996; Glaunes et al., 2004; Hellier and Barillot, 2003). Cortical folding patterns are closely related to brain function and the regional organization of functional areas. The regionalization of cortical function affected by genetic control is important in the development and distribution of cortical convolutions (Rubenstein and Rakic, 1999; Piao et al., 2004; Rakic, 2004). Recently, cortical folding patterns predicted the locations of histologically defined functional areas well (Fischl et al., 2008). Therefore, mathematical representations of cortical folding patterns can play an important role in studying the relationship between cortical morphometry and brain function (Shi et al., 2008).

Many geometric algorithms have been proposed to compute cortical sulci (semi-) automatically from volumes (Tu et al., 2007; Lohmann, 1998; Mangin et al., 1995; Goualher et al., 1999; Rettmann et al., 2002). In particular, a geodesic depth was utilized in the work by (Rettmann et al., 2002). However, extracting cortical sulci and sulcal fundi from magnetic resonance (MR) images is difficult because they have complicated geometric patterns in MR images, which are hard to distinguish from similar patterns caused by other brain structures. With the advancement of cortical segmentation techniques, surface-based approaches are becoming increasingly popular. Local shape measures, such as curvature and torsion (Khaneja et al., 1998), are used to extract sulcal curves on the cortical surface. However, the work by Khaneja et al. (1998) was not fully automatic because it required the start and end points of the sulci to be specified by hand. An active contour model was used in (Vaillant and Davatzikos, 1997), which also needed careful user initialization. Major sulci were detected using learning systems in (Rivire et al., 2002), and these required a learning database manually labeled by a neuroanatomist. An adaptive speed function was used in the fast marching method to extract the sulcal fundi in a semi-automatic way (Tao et al., 2001), but they considered an isotropic distance metric.

To extract sulcal lines automatically from the cortical surface, previous methods used mean curvature (Tao et al., 2002) or isotropic geodesic distance mapping (Shi et al., 2008). The work by Tao et al.

* Corresponding author. Department of Biomedical Engineering, Hanyang University, Korea.
E-mail address: ljm@hanyang.ac.kr (J.-M. Lee).

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(2002) built the statistical shape model of the sulcal line from large data sets and showed intersubject variation. Although local surface shape features were considered in the work by Tao et al. (2002), it assumes surface registration and requires statistical training sets. By computing the Hamilton–Jacobi skeleton (Siddiqi et al., 2002) of the sulcal regions, the method presented in Shi et al. (2008) extracts a network representation of the cortical folding pattern that is homotopic to the sulcal regions. The skeleton extraction approach (Shi et al., 2008) solves an Eikonal equation (a special type of a Hamilton–Jacobi equation) that computes an isotropic geodesic. Although the curvature-dependent weight function is considered in some geodesic computations (Mémoli and Sapiro, 2001; Bronstein et al., 2007), their local distance has also been handled isotropically.

Previous quantitative studies of intersubject variation revealed that the sulcal pattern becomes more consistent and invariant in sulcal fundus regions than in superficial gyral regions, which are more strongly predetermined and retain their identity during development (Lohmann et al., 2008, 1999). It has been suggested that the deepest parts of the sulci not only are ontogenetically important but also have a specific spatial relationship to functional areas. The gyrogenesis theory suggests that areas of rapid growth form gyri at the center of a functional zone, and boundaries between functional areas tend to lie along the sulcal fundi (Hasnain et al., 2001, 2006; Lohmann et al., 2008, Welker, 1990).

Sulcal lines can be defined in various ways depending on specific applications. It is, however, critical for a neuroimaging study to define a sulcal line along the fundic regions with high curvature within a sulcus. Therefore, accurate sulcal lines lie on the valleys of sulcal areas. However, the isotropic distance metric is not adaptive to the shape of a surface. If the sulcal depths are different for a given sulcal line, then the corresponding sulcal line (a bisector curve under the isotropic metric) is not located accurately on the valleys of the sulcal areas (see Fig. 7a and b). It is also important to extract cortical sulci in a robust manner, regardless of the shape variabilities of various human brains acquired from individuals of different ages, sexes, and diseases. A robust computation of the sulcal lines is critical in applications, such as (Fillard et al., 2007), where sulcal lines were used to determine human variabilities. The isotropically computed skeletons, however, depend on the position of the boundaries of the sulcal regions, which results in an inconsistent extraction of the sulcal lines across different human brains. Computing the boundaries between the sulcal and the gyral regions in a consistent way is a challenging problem by itself, because the automatic segmentation algorithm depends on the extraction of outer-hull surfaces, which vary for each human brain. Therefore, we define a "good" sulcal line as one that satisfies the properties of both accuracy and robustness.

The purpose of this paper is to present a new geometric algorithm for automatically extracting sulcal lines on cortical surfaces that is both geometrically accurate and computationally robust. The resulting sulcal lines were utilized in investigating the changes of sulcal shape (average mean curvature and sulcal depth) in AD subjects. Our approach is based on the extraction of anisotropic skeletons for sulcal regions of the cortical surface. Here, the anisotropic geodesic (AG) distance is highly adaptive to the shape of the surfaces because its local distance function is anisotropically controlled by the normal curvature of the surface. By using such an anisotropic metric, the anisotropic skeletons extract cortical sulci lying on the valleys of the sulcal areas and do not vary with local changes in the position of the boundaries between the gyral and the sulcal regions.

Materials and methods

Subjects

The sample for this study consisted of 100 patients with AD who underwent high-resolution T1-weighted volume magnetic resonance imaging (MRI) at the Samsung Medical Center, Seoul, South Korea. All the patients fulfilled the criteria for probable AD proposed by the National Institute of Neurological and Communicative Disorders and Stroke, and the AD and Related Disorders Association (Mckhann et al., 1984). Diagnostic procedures included a clinical interview, a neurological examination, and a series of neuropsychological tests. Laboratory tests, including complete blood count, blood chemistry, vitamin B12/foliate, syphilis serology, and thyroid function tests, did not reveal the cause of the dementia in any of the patients. Conventional MRI brain scans (T1- and T2-weighted, and FLAIR images) confirmed the absence of territorial cerebral infarction, brain tumors, and other structural lesions. The Mini-Mental State Examination (MMSE) (Folstein et al., 1975) was also performed. The control group consisted of 70 healthy volunteers who had no history of neurological or psychiatric illnesses or abnormalities. The cognitive functioning of the control subjects was confirmed to be within normal limits as assessed by MMSE and neuropsychological testing. We obtained informed consents from all the AD patients and controls, and the study was approved by the Institutional Review Board of the Samsung Medical Center.

The demographic and clinical data of the participants are presented in Table 1. The group characteristics were compared using an independent sample t test and a χ^2 test. The age, sex, and years of education did not differ significantly between the groups, but the MMSE scores did.

Cortical surfaces and sulcal regions

Our method for computing the anisotropic skeletons utilizes advanced techniques of cortical surface segmentation because the triangle mesh input has become a reasonably standard form of intermediate result in neuroimaging (Kao et al., 2007). For extracting a 3-D, polyhedral mesh representation of a cortical brain surface, we adapted the Constrained Laplacian-based Automated Segmentation with Proximities (CLASP) algorithm presented by Kim et al. (2005). Many available software packages can be utilized to generate such a surface mesh, including FreeSurfer (Dale et al., 1999), SurfRelax (Larsson, 2001), and BrainVisa (Mangin et al., 2004). The underlying principle of our method works well with closed mesh surfaces produced by all these surface extraction packages.

3-D T1-weighted SPGR echo images were acquired using a 1.5-T MRI scanner (GE Signa, Milwaukee, WI, USA) with the following imaging parameters: coronal slice thickness, 1.5 mm; echo time, 7 ms; repetition time, 30 ms; number of excitations, 1; flip angle, 45°; field of view, 22 ± 22 cm; and matrix size, 256 ± 256 pixels.

Input images are processed using the standard MNI anatomical pipeline. Using a linear transformation, the native MR images are first normalized into a standardized stereotaxic space and then corrected for intensity nonuniformity (Collins et al., 1994; Sled et al., 1998). The registered and corrected volumes are then classified into white and gray matter, cerebrospinal fluid, and background using an advanced neural-net classifier (Zijdenbos et al., 1996). Finally, the CLASP algorithm (Kim et al., 2005; MacDonald et al., 2000) is used to extract the hemispheric surfaces of the inner and outer cortex automatically, and this consists of 40,962 vertices. The accuracy of this technique was

Table 1
Demographic characteristics of controls and AD subjects.

	Control ($n=70$)	AD ($n=100$)	Test[a]	P
Age, years	71.7 ± 4.9	72.3 ± 5.5	−0.65	0.52
Sex, M/F	29/41	37/63	0.34	0.63
Years of education	10.3 ± 4.9	10.2 ± 4.8	0.10	0.92
MMSE score	28.7 ± 1.5	20.2 ± 5.0	12.97	<0.0001

Data for age, years of education and MMSE score: mean ± SD (range).
Data for sex: the number of subjects.
M: Male, F: Female.
[a] Test except for sex (χ^2 test).