Registration of Brainstem Surfaces in Adolescent Idiopathic Scoliosis Using Discrete Ricci Flow

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Abstract. Adolescent Idiopathic Scoliosis (AIS) characterized by the 3D spine deformity affects about 4% schoolchildren worldwide. Several studies have demonstrated the malfunctioning of postural balance, proprioception, and equilibrium control in patients with AIS. Since these functions are closely related to structures in and around the brainstem, the morphometry of the brainstem surface is of utmost importance. In this paper, we propose an effective method to accurately compute the registration between brainstem surfaces. Four consistent features, which describe the global geometry of the brainstem, are automatically extracted to guide the surface registration. Using the discrete Ricci flow method, brainstem surfaces are parameterized conformally onto the quadrilaterally-faced hexahedron, through which the brainstem registration can be obtained. Our registration algorithm can guarantee the exact landmark correspondence between brainstem surfaces. With the obtained registration, a shape energy can be defined to measure the local shape difference between different brainstem surfaces. We have tested our algorithms on 30 real brainstem surfaces extracted from MRIs of 15 normal subjects and 15 AIS patients. Experimental results show the efficacy of the proposed algorithm to register brainstem surfaces, which matches landmark features consistently. The computed registration can be used for the morphometry of brainstems.

1 Introduction

Adolescent idiopathic scoliosis (AIS) is a three-dimensional structural deformity of the spine that occurs during adolescence, and the prevalence is about 4% of the adolescent population worldwide. Due to the lack of generally accepted scientific theory on the etiology of AIS, the treatment and prognosis of AIS are limited [2]. Many experiments and evidences point toward the nervous regulation of the postural balance in the idiopathic scoliosis patients. The brainstem and vestibular system are two key organs in the balance control system. Significant anomalies of the balance function, proprioception and oculomotor reflexes have been reported [3], and morphological difference has been found in the vestibular system [4]. However, there is no reported work on studying the morphological alterations in brain stems in the AIS subjects in an objective and quantitative way. Motivated by this, we are interested in developing mathematical models which facilitate the morphometry of brainstem surfaces in AIS and normal controls.

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In order to perform shape analysis effectively, meaningful one-to-one correspondences between different brainstems must be obtained. Such a process is called *surface registration*. Landmark-matching based registration approaches have been commonly applied, in which landmark features were required to be consistently matched to guide the registration. Landmark-matching registration has shown to be effective in obtaining accurate point-wise correspondences between 3D medical data. On brainstem surfaces, there are no medical features defined by neuroscientists that can be used as a constraint to establish good correspondences. Therefore, in order to register brainstems effectively, meaningful landmark features that describe the global geometry of the brainstem surfaces must firstly be extracted. On brainstem surfaces, four consistent feature curves can be observed, which are basically ridges and valleys with high curvatures. It motivates us to extract out these features to guide for geometric matching brainstem registrations. With these obtained features, landmark-matching registrations can be computed to obtain an accurate point registration that matches geometry as much as possible.

In this paper, we introduce an algorithm to automatically register brainstem surfaces based on the discrete Ricci flow method. Four consistent features are firstly extracted automatically to guide the surface registration. These features effectively describe the global geometry of the brainstem surfaces. Using the discrete Ricci Flow method, brainstem surfaces are parameterized conformally onto the quadrilaterally-faced hexahedron, of which the extracted feature landmarks are mapped to the edges. Quadrilaterally-faced hexahedron is chosen as the parameter domain since the geometry of the brainstem surface is similar to a hexahedron. With that, the distortion under the parameterization can be minimized so that registration can be obtained accurately. Surface registrations between brainstems can then be obtained through the parameterization, which consistently match the feature landmarks. With the obtained registration, a shape energy can be defined to measure the local shape difference between different brainstem surfaces, which is useful to study shape variation between brainstems for the purpose of disease analysis. We tested our algorithm on real brainstem surfaces extracted from MRIs of 15 normal subjects and 15 AIS patients. Experimental results show the efficacy of the proposed algorithms to register and detect the local shape difference between different brainstem surfaces.

Our contributions are two-folded: first, we propose to delineate four salient features on brainstems that describe the global geometry; second, by mapping the four detected landmarks to the four side edges of a hexahedron, we propose an efficient algorithm to conformally parameterize the brainstem surfaces, which naturally induces the registration among brainstem surfaces. Our registration algorithm can guarantee the exact landmark feature correspondence.

2 Previous Work

Surface registration, which aims to find a meaningful 1-1 correspondence between different surfaces, has been studied extensively by different groups. Conformal surface registration is commonly used [8][9], which gives a parameterization minimizing the angular distortions. An advantage of this approach is that they preserve local geometry very well. Conformal structure can also measure non-isotropic deformation effectively.

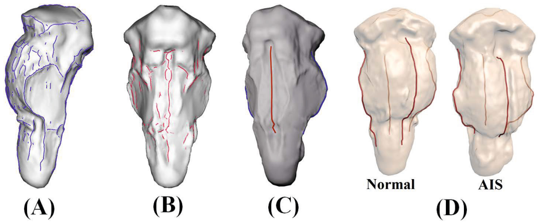

Fig. 1. Landmark extraction. (A) and (B) show the computed ridge and valley lines respectively. The two strongest ridge and valley lines are chosen as landmarks, as shown in (C). (D) shows the four consistent features extracted on brainstems of a normal and an AIS subject.

However, conformal registrations generally cannot map landmark features, such as sulcal landmarks on brain surfaces, consistently. Landmark-based diffeomorphisms are often used to compute, or adjust, cortical surface parameterizations [7,11]. For example, Glaunes et al. [7] proposed to generate large deformation diffeomorphisms of the sphere onto itself, given the displacements of a finite set of template landmarks. Leow et al. [11] proposed a level-set based approach to match different types of features, including points and 2D or 3D curves represented as implicit functions. These methods provide good registrations when the corresponding landmark points on the surfaces can be labeled in advance. On surfaces without well-defined landmarks, some authors have proposed driving features into correspondence based on shape information. Lyttelton et al. [13] computed surface parameterizations that match surface curvature. Fischl et al. [6] improved the alignment of cortical folding patterns by minimizing the mean squared difference between the average convexity across a set of subjects and that of the individual. Lord et al. [12] matched surfaces by minimizing the deviation from isometry.

3 Algorithm

3.1 Overview

Given the brainstem surface M, we first detect four salient geometric features on M. We then apply the discrete Ricci flow method to parameterize the brainstem surfaces onto a quadrilaterally-faced hexahedron, through which the four feature curves on the brainstem are mapped to the four vertical sides of the hexahedron. As our parameterization method naturally segments the brainstem surfaces into six patches, we can easily register two different brainstems by finding a diffeomorphism between each corresponding patches. In the following, we explain each step in details.

3.2 Landmark Extraction

On brainstem surfaces, four consistent features can be extracted, which are essentially curves with high surface curvatures. We extract these features by computing the ridge-valley lines [1], an effective shape descriptor on the surface along which the surface

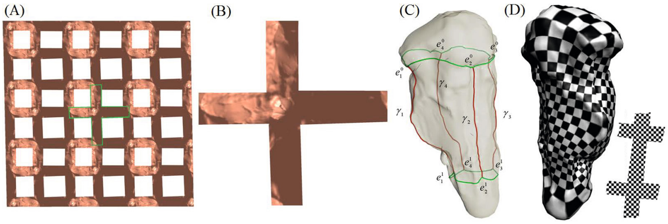

Fig. 2. The cut surface can be conformally embedded into the universal covering as shown in (A). (B) shows the fundamental domain (one period) of the universal covering.The parameterization naturally induces a segmentation of the brainstem surfaces into six patches as shown in (C). In (D), the checkerboard texture on the parameter domain is mapped to the brainstem surface, which mapping shows the parameterization is indeed conformal.

bends sharply. Figure 1(A) and (B) show the computed ridge-valley lines on a brainstem surface. After obtaining the ridge-valley lines, we smooth them using a Gaussian filter (with kernel size 2% of the main diagonal of the object's bounding box) to reduce the artifacts caused by the noise and/or poor triangulation. The detected ridges or valleys are merged, if their endpoints are close and their tangent directions are within the user-specified threshold. In our implementation, we set the distance and direction thresholds to 2% of the object's main diagonal and 15 degree respectively. Next, we measure the strength of each feature by computing the length of the detected ridge-valley line. The longer the curve, the stronger the feature. We then find the two strongest ridges and valleys, which are chosen as landmark features. On brainstem surfaces, there are consistent umbilic points and high-curvature points. These points are chosen as the endpoints of the landmark features. Fig. 1(C) shows the strongest ridge and valley lines extracted.

Among the four landmarks, we observed the two feature lines in the valley γ_2 and γ_4 are quite robust and consistent, since their end points fall in regions with highly negative mean curvatures. For the other two ridges γ_1 and γ_3, their locations are consistent, but their end points may differ among the subjects. To solve this issue, we specify the length of the ridges so that the tracing stops immediately when the landmark exceeds the threshold. We also allow the users to specify the end points manually. Fig. 1(D) shows the four consistent features extracted on brainstems of a normal and an AIS subject.

3.3 Parameterization Using Discrete Ricci Flow

To ease the computation process, we parameterize the brainstem onto a domain in $\mathbb{R}^2$. The ideal parameter domain for such surface is the quadrilaterally-faced hexahedron, of which each landmark is mapped to an edge of the hexahedron. Discrete Ricci flow method is used to obtain the parameterization.

Given a brainstem surface, we first cut it open along the detected feature lines. As a result, the open brainstem surface is of genus 0 with 4 boundaries, denoted by γ_i, $i = 1, ..., 4$. We then set the target curvatures to be $-\pi/2$ at the end points of the landmarks and zero elsewhere. Using the discrete Ricci flow method [10], we can parameterize the brainstem surfaces onto the universal covering space embedded in $\mathbb{R}^2$.

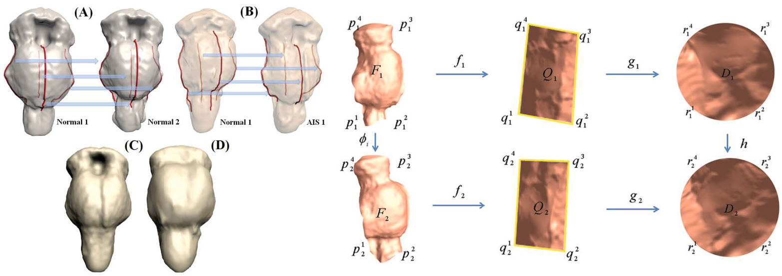

Fig. 3. Left: (A) Registration between two normal brainstems. (B) Registration between the brainstems of a normal and AIS subject. Landmark features are matched exactly. (C) shows the average shape of 15 AIS brainstems using our registration. The sharp features are well-preserved after averaging, meaning that our registration matches salient features well. (D) shows the average shape using the curvature-based sphereical demons registration without landmarks [15]. Note that the sharp features are smoothed out. Right:Computing the map $\phi_i : F_1^i \to F_2^i$.

To visualize the parameterization, we cut the brainstem surface along the geodesics (i.e. line segments) $e_1^1 e_2^1$, $e_2^1 e_3^1$, and $e_3^1 e_4^1$ (see Fig. 2(C)), under the new metric $\overline{g}$. Intuitively speaking, we cut along the edges of the bottom face to make the hexahedron open. Now the brainstem surface becomes a genus-0 surface with only one boundary.

We compute the layout of the parameterized mesh by isometrically embedding all the triangles with the new metric $\overline{g}$. Figure 2 shows the universal covering space of the brainstem surface with the highlighted fundamental domain. One can see that each landmark is mapped to the straight side of the hexahedron. This feature allows us to easily compute the high quality registration with guaranteed exact landmark matching, which will be described in the next subsection.

3.4 Registration

The above discrete Ricci flow method parameterizes each brainstem surface to a hexahedron, such that the four landmarks are mapped to the four vertical edges. The hexahedron naturally induces a segmentation of 6 patches. With these, we can easily register two brainstem surfaces in a piecewise manner.

Let F_1^i (resp. F_2^i), $i = 1, \cdots, 6$, denote the six patches of M_1 (resp. M_2) induced by the parameterization. We want to find a diffeomorphism (i.e., a C^∞-smooth and bijective map) $\phi_i : F_1^i \to F_2^i$ between each pair of patches F_1^i and F_2^i. Let f_1 (resp. f_2) denote the Ricci flow parameterization that maps F_1^i (resp. F_2^i) to a quadrilateral D_1^i (resp. D_2^i). Let us also denote the corners of the 3D patch and 2D quadrilateral by p^j and q^j, $j = 1, \cdots, 4$, respectively. Then we map each quadrilateral Q to a unit disc D by a harmonic function $g : Q \to D$ such that $\triangle g = 0$ with Dirichlet boundary condition $g(\partial Q) = \partial D = \mathbb{S}^1$. Let $r^j = f(q^j)$, $j = 1, \cdots, 4$, denote the images of the corners on the unit circle. Next, we compute another harmonic function $h : D_1^i \to D_2^i$ between the two unit discs D_1^i and D_2^i, i.e., $\triangle h = 0$. We set the boundary condition $h(\partial D_1^i) = \partial D_2^i$ by enforcing the exact feature correspondence, i.e., the corners r_1^j

are mapped to corners r_2^j. Therefore, a map ϕ_i between the patches F_1^i and F_2^i can be obtained by the composite map $\phi_i = f_2^{-1} \circ g_2^{-1} \circ h \circ g_1 \circ f_1$ (See Fig. 3) right.

A homeomorphism $\phi : M_1 \to M_2$ can then be obtained by $\phi = \bigcup_{i=1}^{6} \phi$. Note that landmarks are exactly matched for each patches. So, our algorithm guarantees the exact correspondence between the landmark features.

Proposition. The proposed brainstem surface registration algorithm produces a homeomorphism ϕ between M_1 and M_2, which guarantees the exact correspondence between the landmarks $\phi(\gamma_1^j) = \gamma_2^j, j = 1, \cdots, 4$.

Proof. We first show that the resulting map ϕ is a homeomorphism. Observe that the discrete Ricci flow induced parameterization f_1 and f_2 are diffeomorphism [5]. According to the classical result [14], a harmonic function, which maps a $\Omega \subset \mathbb{R}^2$ to some convex region Ω' and maps the the boundary $\partial\Omega$ homeomorphically into the boundary $\partial\Omega'$, is diffeomorphic. As Q_j and $D_j, j = 1, 2$, are convex and the boundary conditions in g_j and h are homeomorphic, all the harmonic functions g_1, g_2 and h are diffeomorphic. Therefore, the map $\phi_i = f_2^{-1} \circ g_2^{-1} \circ h \circ g_1 \circ f_1$ is a diffeomorphism (see Fig. 3) right.

Although the maps ϕ_i's are calculated individually, they can be glued seamlessly. We use the arc-length parameterized boundary condition in computing the harmonic map from each patch to the unit disk. Assume two patches F_a and F_b share a boundary γ, and $p \in \gamma$ is an arbitrary point on γ. When we compute the map g from F_a to the unit disk, we set the Dirichlet boundary condition so that p's image is given by the arc-length parameterization. Similarly, the map from F_b to the unit disk also sends p to exactly the same location on the circle. With this, our method can guarantee the boundaries of two adjacent patches are mapped consistently and thus all patches are glued seamlessly in a C^0 manner. Thus, the global map, $\phi = \bigcup_i^6 \phi_i$, is in fact a homeomorphism.

Second, we show that the map ϕ preserves the correspondence between the landmarks. By setting the prescribed geodesic curvature on γ_1^j and γ_2^j to zero, $j = 1, \cdots, 4$, the metric $g(\infty)$ obtained by discrete Ricci flow can guarantee each landmark is mapped to a *line segment* (see Fig. 2(b)). Then with harmonic functions, g_1 and g_2, each line segment is mapped to an arc of the unit circle. Note that the exact feature correspondence are set when computing the harmonic function $h : D_1 \to D_2$ between two unit disks. Therefore, the composite function ϕ_i maps the boundary ∂F_1 homeomorphically to ∂F_2 and also sends each corner of F_1 to the corresponding corner of F_2. Thus, the map ϕ_i sends the landmark of F_1 to the corresponding landmark of F_2. As a result, the map ϕ preserves the exact correspondence between the landmarks $\phi(\gamma_1^j) = \gamma_2^j$, $j = 1, \cdots, 4$.

Putting it together, the map $\phi : M_1 \to M_2$ is a homeomorphism with guaranteed landmark correspondence. $\square$

3.5 Shape Variation Detection

With the obtained registration between brainstems, we can define a shape energy which detect local shape variations. According to Riemannian geometry theories, the local geometry of a Riemann surface can be described by its mean curvature and Gaussian curvature. Let B_1 and B_2 be two brainstem surfaces. Suppose $f : B_1 \to B_2$

Input: Two brainstem surfaces M_1 and M_2
Output: The homeomorphism $\phi : M_1 \to M_2$ with guaranteed landmark correspondence
1. Extract the four landmarks from the brainstem surfaces;
2. Cut the brainstem surfaces open along the detected landmarks;
3. Set the prescribed Gaussian and geodesic curvatures to each vertex and run Ricci flow;
4. With the resulting metric, embed the brainstem surfaces into quadrilaterally-faced hexahedral, which naturally induces a segmentation of M_1 and M_2 into six patches.
5. For each pair of patches $F_1^i \in M_1$ and $F_2^i \in M_2$, find the bijective map $\phi_i : F_1^i \to F_2^i$ by computing harmonic functions with Dirichlet boundary conditions;
6. Output the map $\phi = \bigcup_{i=1}^6 \phi_i$.

Algorithm 1. Brainstem surfaces registration with guaranteed landmark correspondence.

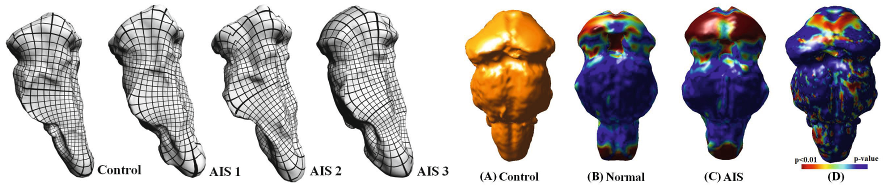

Fig. 4. (A)-(D): Grid texture is drawn on the control brainstem. It is mapped to three different brainstems of the AIS subjects using our proposed registration algorithm. The grid pattern illustrates that our registration result is indeed an homeomorphism. (E)-(H):Detection of shape variations.

is the registration between B_1 and B_2. We can define a shape energy E_{shape} as follows: $E_{shape}(f) = \alpha \int_{B_1} |H_1 - H_2(f))| + \beta \int_{B_1} |K_1 - K_2(f))|$, where H_1 and K_1 (resp. H_2 and K_2) are the mean curvature and Gaussian curvature of B_1 (resp. B_2). $E_{shape}(f) = 0$ if and only if B_1 and B_2 are equal up to a rigid motion. Therefore, E_{shape} measures the local shape difference between B_1 and B_2 effectively. This allows us to examine the region of significant shape difference for the morphometry of the brainstems.

4 Experimental Results

Subject and data acquisition: We tested our proposed algorithms on 30 brainstem surfaces, which are extracted from the MRIs. The MRI brain data were acquired from 15 AIS subjects and 15 age-matched normal controls using a 1.5T MRI scanner (Sonata, Siemens, Erlanger, Germany) using a quadrature head-coil. The segmentation of the brain stems was achieved automatically. Two experienced operators verified the segmentation results.

Brainstem registration: Using our proposed algorithms, we compute the registration between 30 brainstems of 15 normal subjects and 15 AIS patients. Experimental results show that our proposed method can compute the registration effectively with exact landmark-matching. Figure 3(A) shows the registration results between two normal brainstems. The registration result between the brainstems of a normal and AIS subject is shown in (B). Landmark features are exactly matched. In Fig. 4(A)-(D), grid texture is drawn on the control brainstem. It is mapped to three different brainstems of the AIS subjects using our proposed registration algorithm. Note that grid patterns have no overlapping, indicating the registration is indeed a homeomorphism. The whole registration procedure can be computed efficiently. The feature landmarks (ridge and valley lines) are computed in real-time for brainstem meshes with 20K vertices. The Ricci flow based conformal parameterization for each brainstem mesh takes about 12 seconds, since the Newton's method with second order convergence rate is adopted in our implementation. The registration between brainstems through the parameterization takes about 5 seconds to compute. The whole process to obtain the landmark-matching brainstem registration takes less than 20 seconds. Hence, our proposed registration algorithm is quite efficient.

Detection of shape variations: With the obtained registration f, the local shape difference between different brainstem surface can be detected from the shape energy $E_{shape}(f)$. Figure 4(E)-(H) shows the local shape differences of two brainstem (1 normal and 1 AIS subject) surfaces from the control. The color map is given by the shape energy, which measures their local shape difference. The red (resp. blue) color indicates a higher (resp. lower) degree of shape difference. The local shape difference of the AIS brainstem from the control tends to be more obvious than that of the normal brainstem. Figure 4(H) shows the statistical significance p-map measuring the local shape difference from the control between the normal ($n = 15$) and AIS ($n = 15$) groups, plotted on a control brainstem. The deep red color highlights regions of significant statistical difference. This method can be potentially used to study factors that influence shape changes of brainstems in AIS.

Comparison: We also compare our registration algorithm with the curvature-based spherical demons registration without landmarks [15]. The curvature-based registration without landmarks generally cannot match salient features. Figure 3(C) shows the average shape of 15 AIS brainstems using our registration. The sharp features are well-preserved after averaging, meaning that our registration matches salient features well. (D) shows the average shape using the curvature-based registration without landmarks. Note that the sharp features are smoothed out. It indicates the mismatching of salient features.

5 Conclusion and Future Work

We present a rigorous algorithm to register brainstem surfaces for the disease analysis of Adolescent Idiopathic Scoliosis. The basic idea is to extract four consistent features, which describe the global geometry of the brainstem, to guide the surface registration. Using the Ricci Flow method, brainstem surfaces are parameterized conformally onto quadrilaterally-faced hexahedron, which naturally induces the feature landmark-matching brainstem registration. Our registration algorithm is a registration between brainstem surfaces with exact matching of the extracted feature curves. A shape energy can then be defined to measure the local shape variations between different brainstem surfaces. Experiments on real brainstem surfaces of 15 normal subjects and 15 AIS patients show the efficacy of our proposed algorithms to register and detect local shape differences between different brainstem surfaces. The proposed algorithm can potentially be used to study factors that influence shape changes of brainstems in AIS. For future work, we will apply our proposed algorithms on more brainstem data to further investigate the relationship between the postural balance control problem and the occurrence of AIS. We would also like to point out that the proposed algorithm can be naturally extended for registration of other anatomical structures, such as hippocampus, cerebellum and the vestibular system, which will be investigated in our future work.

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