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# Automatic registration of vestibular systems with exact landmark correspondence

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ABSTRACT

Shape registration has a wide range of applications in geometric modeling, medical imaging, and computer vision. This paper focuses on the registration of the genus-3 vestibular systems and studies the geometric differences between the normal and Adolescent Idiopathic Scoliosis (AIS) groups. The non-trivial topology of the VS poses great technical challenges to the geometric analysis. To tackle these challenges, we present an effective and practical solution to register the vestibular systems. We first extract six geodesic landmarks for the VS, which are stable, intrinsic, and insensitive to the VS's resolution and tessellation. Moreover, they are highly consistent regardless of the AIS and normal groups. The detected geodesic landmarks partition the VS into three patches, a topological annulus and two topological disks. For each pair of patches of the AIS subject and the control, we compute a bijective map using the holomorphic 1-form and harmonic map techniques. With a carefully designed boundary condition, the three individual maps can be glued in a seamless manner so that the resulting registration is a homeomorphism with exact landmark matching. Our method is robust, automatic and efficient. It takes only a few seconds on a low-end PC, which significantly outperforms the non-rigid ICP algorithm. We conducted a student's $t$-test on the test data. Computational results show that using the mean curvature measure $E_H$, our method can distinguish the AIS subjects and the normal subjects.

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## 1. Introduction

Surface registration is the process that aligns a source 3D surface to a target. It has a wide range of applications in geometric modeling, medical imaging, and computer vision. This paper focuses on registration of the vestibular systems (VS) and studies the geometric differences between the normal and Adolescent Idiopathic Scoliosis (AIS) groups. The vestibular system is the sensory system situated in the inner ear, which contributes to balance and the sense of spatial orientation. The VS is a genus-3 structure with three semicircular canals (see Fig. 1)) and the morphometry of VS plays an important role in the analysis of various diseases such as the AIS disease, which is a 3D spinal deformity affecting about 4% school children worldwide. The etiology of AIS is still unclear but believed

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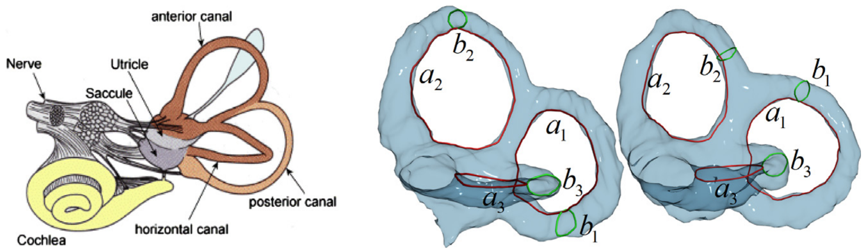


(a) The labyrinth of the inner ear (courtesy of wikipedia)

(b) The homology basis of the genus-3 VS

**Fig. 1.** The vestibular system is a genus-3 structure (colored in brown) in the inner ear. Its homology basis $\{a_i, b_i\}_{i=1}^{3}$ of the genus-3 vestibular system contains 6 loops. Among them, the three geodesic *tunnel* loops $a_i$ are highly consistent regardless of the AIS/normal subjects. The locations of the geodesic *handle* loops $b_i$, however, may vary significantly. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

to be a multi-factorial disease. One popular hypothesis was suggested to be the structural changes in the VS that induce the disturbed balance perception, and further cause the spinal deformity [1,2]. Some recent works have revealed the statistical differences in global morphology of the VS between right-thoracic AIS and normal controls [3,4]. In order to perform shape analysis effectively, meaningful one-to-one correspondence between different VSs must be obtained. Landmark-matching based registration techniques, in which landmark features were required to be consistently matched to guide the registration, have proven to be effective in obtaining accurate point-wise correspondences between 3D medical data. However, the non-trivial topology of the VS poses great challenges for the landmark based registration. The existing surface registration algorithms either work only for shapes with simple topology (e.g., simply or multiply connected domains) or are too time consuming and memory inefficient, which are not suitable for our problem.

This paper presents a computational framework to register the vestibular systems. Our contributions are two-folded:

- First, we present a robust algorithm to extract the salient geodesic landmark features from the vestibular systems. Thanks to its intrinsic nature, the geodesic landmarks are totally determined by the metric and are highly consistent regardless of the AIS and normal groups.
- Second, we present an efficient algorithm to register the vestibular systems with exact landmark correspondence. We first partition each VS into three patches, a topological annulus and two topological disks, using the extracted landmark features. Then for each pair of patches of the AIS subject and the control, we compute a bijective map using the holomorphic 1-form and harmonic map techniques. With a carefully designed boundary condition, the three individual maps can be glued in a seamless manner. The resulting registration is guaranteed to be a homeomorphism with exact landmark correspondence.

To our knowledge, this is the first work to address the landmark based registration of the vestibular systems. Our method is robust, automatic and efficient, which takes only a few seconds on a low-end PC. We have tested our algorithms on 13 normal subjects and 15 AIS patients. Computational results show that our method can distinguish the AIS subjects and normal subjects by using the mean curvature measure.

## 2. Related work

As a fundamental problem in medical imaging, digital geometry processing and graphics, surface registration has been studied extensively in the past two decades. Most of the existing registration algorithms focus on rigid registration, where the motion between the source and the target is rigid. Representative work is the iterative closest point (ICP) algorithm [5], which iteratively computes correspondence between the source and the target, and performs a rigid motion in response to these correspondences. Rigid registration and non-rigid registration under small deformation are ideal for 3D scanning systems, in which the source and the target are the overlapped scans of static model. However, they are not suitable for our problem, where the deformation between the source and the target could be large.

Recently, non-rigid registration dealing with large deformation has attracted increasing attention. Huang et al. [6] formulated non-rigid registration as an optimization problem and solved it by alternating correspondence computation and deformation optimization in terms of the resulting correspondences. By enforcing the geodesic distances between sets of corresponding points, their method is highly stable and works well for aligning partially overlapping point clouds, which are sampled from models under isometric deformation. However, the mapping between two VS surfaces are in general not isometric, their method cannot be applied to our problem.

Amberg et al. [7] proposed the optimal step non-rigid ICP algorithm, which recovers global and local deformations of the mesh by successive application of ICP. Starting with a stiff template, the algorithm successively relaxes the stiffness to recover more local deformations. To find the optimal deformation for a given stiffness, optimal iterative closest point steps are used. Their method can

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