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# Free-form image registration of human cochlear $\mu$CT data using skeleton similarity as anatomical prior☆

H. Martin Kjer[a,*], Jens Fagertun[a], Sergio Vera[b,c], Debora Gil[c,f], Miguel Ángel González Ballester[d,e], Rasmus R. Paulsen[a]

[a] Department of Applied Mathematics and Computer Science, Technical University of Denmark, Copenhagen, Denmark
[b] Alma IT Systems, Barcelona, Spain
[c] Computer Vision Center, Universitat Autònoma de Barcelona, Barcelona, Spain
[d] Department of Information and Communication Technologies, Universitat Pompeu Fabra, Barcelona, Spain
[e] Institució Catalana de Recerca i Estudis Avançats (ICREA), Barcelona, Spain
[f] Serra Húnter fellow

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ABSTRACT

Better understanding of the anatomical variability of the human cochlear is important for the design and function of Cochlear Implants. Proper non-rigid alignment of high-resolution cochlear $\mu$CT data is a challenge for the typical cubic B-spline registration model. In this paper we study one way of incorporating skeleton-based similarity as an anatomical registration prior. We extract a centerline skeleton of the cochlear spiral, and generate corresponding parametric pseudo-landmarks between samples. These correspondences are included in the cost function of a typical cubic B-spline registration model to provide a more global guidance of the alignment. The resulting registrations are evaluated using different metrics for accuracy and model behavior, and compared to the results of a registration without the prior.

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## 1. Introduction

Image registration and establishment of correspondences between data is a common challenge in biomedical image analysis. The best registration model is largely case-dependent, influenced by the anatomy, the involved imaging modalities, the desired end-goal, etc. [11,17,18]. In cases that require large and complex deformations finding the optimal registration procedure becomes a challenging task. As the amount of parameters in the transformation model increases it becomes more and more difficult for the optimization to avoid local minima. In these cases, it is often required to include some additional prior knowledge or regularization/constraints to efficiently solve the registration.

The challenging case presented in this paper is the task of registering data of the (human) inner ear. This structure controls the sensation of hearing and balance, and an understanding of the anatomy and anatomical variability plays an important part in utilizing the full potential of Cochlear Implants [30]. Detailed anatomical models have interesting patient-specific applications as they can provide information about the type of electrode design that suits the anatomy of the user [29], or by allowing improvements to the implant programming based on simulations mimicking the actual anatomical and physiological situation [6].

The anatomy of the inner ear is composed of the vestibular system and the cochlea. Image registration of the latter is challenging for a couple of reasons, and will be the focus of this work. The human cochlea is a spiral structure with outer dimensions of approximately $10\times8\times4$ mm. The size and the shape of the spiral can vary extensively. On average, the cochlea winds 2.6 turns [9] but can approach up to three full turns – corresponding to a difference in the order of 1–2 mm following the path of the spiral. The separation between the cochlear turns is typically one order of magnitude smaller. Specially deformations to properly align the most apical region of spiral have been difficult to model to our experience. Further, the whole spiral is a tube-like structure (see Fig. 1, right) with a large degree of self-similarity in the cross-sections. This lack of distinct features makes it difficult to identify corresponding anatomical positions across samples.

The desired registration model should not just expand or compress the apical part of the spiral to align two samples, but rather

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* Corresponding author. Tel.: +4545255228.
*E-mail address:* hmkj@dtu.dk (H.M. Kjer).

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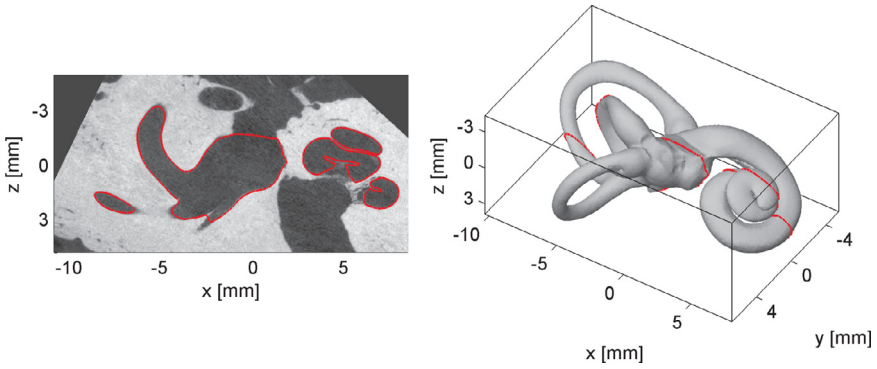


**Fig. 1.** Left: Impression of the $\mu$CT data and segmentation (red border). Notice the small spacing separating the cochlear turns (right side of CT image), the weak contrast towards internal cochlea borders, and the opening into the middle ear cavity (middle of the image). Right: The corresponding surface model provides an overview of the inner ear topology. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

model a change along the entire spiral. Essentially the model should be able to handle very local deformations while still adhering to the global structure of the samples. This type of behavior is usually not native to non-rigid registration models without some kind of prior or regularization included.

Modifications to a registration model to include such prior knowledge have been studied previously. A way of introducing anatomical shape priors is the use of a statistical shape model [4,10]. However, building statistical shape models is in itself a labor intensive task rivaling if not surpassing the task of the registration, as the prerequisite for building the model is data that is already registered to have correspondences.

A multitude of physical constraints have also been proposed as regularizations. For example, local tissue rigidity can be enforced in specified areas [23], or conditions of incompressibility or volume-preservation can be applied [20]. However, finding the suitable physical constraint for a registration task is not straightforward, as this is case- and application dependent.

In the work of [3] an articulated skeleton model was pre-registered to intra-mouse data studies in order to recover large pose-differences between data acquisitions. The presented application is narrow in its scope, but the registration methodology of using landmark correspondences as regularization is more generally applicable, thus we adopt this approach for this work.

In this paper we explore the potential of using the skeleton of a surface object as an anatomical prior in free-form registrations using a B-spline transformation model.

Skeletonization of a volume or surface is a research field in itself [7,22]. The skeleton provides a global description of shape in a simplified and structured form. Matching based on skeleton similarity could provide a global anatomical guidance or regularization to a locally defined free-form image registration procedure with a high resistance to noise compared to using only the image intensity similarity. The use of skeleton similarity in image registrations should be applicable to many different problems and there are many published methods and approaches for finding and matching the skeletons for differing types of data and geometries [24,26]. Skeleton correspondence has been seen in image registration tasks before, relating to for instance 2D/3D multi-modal registration [15] and matching of vessels in time-series angiography data [27]. More related to our approach is the work of [25], where multiple different shape features were calculated from surface objects and transformed into vector-valued 2D feature images, which were aligned with a classic image registration formulation. Skeleton features were used for global alignment in the coarser levels of the registration. Our strategy is similar although the prior will be included into the registration model differently.

The purpose of this study is to test and evaluate deformable registration using a B-spline transformation model on a series of inner ear datasets with/without the use of skeleton-based similarity in the registration model.

The rest of the paper is structured as follows. Section 2.1 provides a description of the data and the processing, and Section 2.2 contains the procedure for finding skeletons and their similarity across datasets. The registration models and their evaluation are detailed in Sections 2.3 and 2.4 respectively. The results are presented in Section 3 and discussed in Section 4.

## 2. Material and methods

### 2.1. Data and processing

A collection of 17 dried temporal bones from the University of Bern were prepared and scanned with a Scanco Medical $\mu$CT100 system. The data was reconstructed and processed to obtain image volumes of 24 micron isotropic voxel-sizes containing the inner ear (Fig. 1, left).

**Image segmentation:** The border of the inner ear was segmented in all datasets semi-automatically using ITK-SNAP [31]. On standard CT images the cochlear will appear to have a circular cross-section. Due to the higher resolution of $\mu$CT and the sample preparation it becomes possible to see the *lamina spiralis*. It is a bony ridge structure that traverses the entire cochlea from the spiral central direction, partially separating the cochlear into two chambers (*scala tympani* and *scala vestibuli*) and creating a 'U'-shaped cross-section (see Fig. 1, left). The semi-automatic tool in the segmentation software was critical for achieving smooth and rounded segmentations in data with that kind of resolution, and for reducing the amount of manual work. The images contain some openings, less well-defined regions and non-anatomical artifacts that had to be manually handled to obtain comparable segmentations across datasets. For this reason a segmentation of one dataset easily amounts to 12–15 h, but it is a requirement for having a ground truth and a correct representation of the object. A surface model was generated for each dataset using Marching Cubes [16] followed by a surface reconstruction [19] to obtain a well-formed triangular mesh (Fig. 1, right).

### 2.2. Skeletonization

Implementing and comparing skeletonization methodologies is not the scope of this work. Our aim is to find a simple method for generating skeleton correspondence between samples that can easily be included in a registration model thus allowing us to explore the potential of the approach. The object topology is an important consideration when working with skeletons, as this poses a restriction for certain methods. To avoid working with a genus 3 surface, we exclude the vestibular system and focus only on a skeleton of the spiral shaped cochlea.

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