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Estimation of the deformations induced by articulated bodies: Registration of the spinal column

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Abstract

We present a new non-rigid registration algorithm estimating the displacement field generated by articulated bodies. Indeed the bony structures between different patient images may rigidly move while other tissues may deform in a more complex way. Our algorithm tracks the displacement induced in the column by a movement of the patient between two acquisitions. The volumetric deformation field in the whole body is then inferred from those displacements using a linear elastic biomechanical finite element model. We demonstrate in this paper that this method provides accurate results on 3D sets of computed tomography (CT), MR and positron emission tomography (PET) images and that the results of the registration algorithm show significant decreases in the mean, min and max errors.

Keywords: Articulation; Vertebrae; Registration

1. Introduction

1.1. Image guided radiotherapy

In radiation oncology, the development of new algorithms for three-dimensional dose calculation along with computer driven linear accelerators able to deliver intensity modulated radiation beams have made it possible to sculpt the radiation dose precisely to target volumes of almost any shape (see Webb [1]). Improvement in the physical dose distribution obtained by the procedure referred to as intensity-modulated radiation therapy (IMRT) has raised the critical issues of the adequacy and accuracy of the selection and delineation of the target volumes on a 3D-basis. In this context more delineations of the tumor and of the different organs should be taken into account to improve patient therapy. Unfortunately, tumors boundaries in the neck area are differently defined on each imaging modality (anatomical images such as the computed tomography (CT) scan, magnetic resonance imaging (MRI) or functional images such as the positron emission tomography (PET) scan). The patient's treatment follow-up would be enhanced if previous delineations could be transferred onto new images to take account of previous radiation doses for subsequent scheduling. Furthermore it would save time to avoid completely new manual segmentations for the following radiation sessions and to enable the user to restart his delineations from previous segmentations. For these reasons, registration methods are increasingly important in clinical routine to transfer information between images and modalities. In the neck area, registration methods need to take rigid structures into account. Very few methods able to deal with multimodal images, volumetric registration and multiple elasticities have been proposed, and not for the neck area.

In this work, the multimodal images of the neck to be processed induce different choices of deformation models. Indeed the following features have to be taken into account:

- The methods registering the surfaces need smooth surfaces, but vertebrae have complex shapes. Furthermore, these

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methods must have segmentations of quality of both images. We would like to segment the first acquired image only and be able to register the new images acquired during the therapy without having to segment them.
- Volumetric deformations must take the rigid structures into account without deforming them. 3D basis functions, for instance, do not allow one to move or rotate complex rigid structures without distorting them.
- The method must be multimodal and some large deformations may lead to the choice of a metric computed on the whole image.

1.2. Non-rigid registration including different elasticities

Different groups have studied registration methods taking bodies with different elasticities into account. We present in this section their work and why we cannot use their methods for our neck application.

Ferrant et al. proposed to register segmented surfaces and to propagate the deformation inferred from the registration using a linear elastic biomechanical finite element model [2] or using an elastic warping [3]. These methods achieve good results in the brain region but need segmentations in both moving and target images. Furthermore, the surfaces to be matched have to be smooth. This hypothesis is sufficient for brain images but too constraining for spinal column images.

Rueckert et al. proposed a volumetric registration method combining B-spline transformation and mutual information [4]. These B-splines were placed on a regular grid and allowed to deform the moving images gently. Dawant and co-workers proposed to relax the constraints between B-splines to model different elasticities. Nevertheless, the method does not allow one to move rigid structures such as bones without deforming them [5].

Lester presents a modified fluid algorithm incorporating inhomogeneities [6]. The viscous fluid algorithm is a PDE summarized by the Stokes equation. The inhomogeneities are introduced by modifying this viscosity parameter. The method proposed is monomodal.

Hagemann et al. proposed a transformation coupling fluid and elastic models with different elasticities to model landmark-based deformations in the head area. They combined the Navier equation for multielastic behaviours and the Stokes equation for incompressible fluids. The use of landmarks to constrain a deformation can be very constraining [7].

Arsigny et al. proposed a method searching the translations and rotations to apply to control points, the voxels being interpolated using weight functions. This method has been tested on 2D histological slices of the brain, but still needs a lot of work to be exported to 3D [8].

The finite element-based approach proposed by Gee and co-workers [9–11] and implemented in ITK [12,13] estimates the forces to apply by computing the gradient of the mutual information locally and solving Hooke Law (or the stiffness equation) at each iteration of their algorithm. This approach requires solving a time-consuming linear finite element system at each iteration. Moreover, a volumetric force distribution has to be derived from a local similarity metric.

While a lot of literature exists about registration methods for soft tissues such as the brain or the liver, fewer methods present techniques taking rigid tissues such as bones in the neck area into account. Little has proposed a two-dimensional method using landmarks constraining a transformation [14]. This transformation consists of radial basis functions that are modified by the use of distance transformations based on rigid structures, but this method has never been exported to three dimensions.

One proposed model of the cervical spine used many manually placed springs (see Furukawa et al. [15]), but it takes a lot of time to place eight springs between two consecutive vertebrae. Only a few people have proposed combining both an articulated model and registration. Loutas et al. has proposed an articulated registration method based on a simple kinematic model using a Kalman filtering scheme for arm and finger tracking in 2D video sequences [16]. Recently another articulated method has been proposed (see ref. [17]) to register two-dimensional X-ray images of the hand. They propose to impose the displacement of each node of their model of the hand manually and to propagate the displacement by a mathematical shape function. Finally Shen et al. (see refs. [18,19]) proposed to include a spring mass system to model the deformation of the articulated structures and to aply it to 2D images.

1.3. Contributions

We propose to model an articulated structure composed of elements and nodes and to embed this articulated model in a registration scheme. We propose to apply this 3D articulated registration method to multimodal images of the cervical spine. Our method is composed of two main steps:

1. Our strategy allows the registration of the vertebral column thanks to an articulated model. We describe the kinematic model of the spine by an articulated structure composed of elements and nodes having three degrees of freedom. This follows the theory that a vertebra does not slide but rotates around its axis (see Monheit and Badler [20]). The method searches for the best parameters of the articulated transformation to maximize the mutual information, which is a global similarity metric. The articulated transformation we developed constrains the vertebrae to move relative to their neighbours.
2. The articulated transformation is undefined outside the chained elements of the articulation. For this reason we propose to propagate the deformation to the whole image through a coupled linear elastic model. We achieved fast accurate results using an adaptive multiresolution mesh. A mesh can incorporate local physical information such as elasticity or statistical prior knowledge. This way, it allows the inclusion of information regarding the nature of the object being represented in the registration process.

The first section describes the articulated transformation and registration. The second section describes the propagation