Piecewise Rigid Multimodal Spine Registration

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Abstract. In this paper we present an efficient and robust vertebra segmentation algorithm for CT data. It proved reliable even for cases with damaged vertebrae or missing intervertebral discs. The resulting segmentation is then used to define the corresponding regions of interest in a piecewise rigid registration of the spine between CT and MR datasets of the same patient. The resulting deformation field has been extended to the surrounding soft tissue by smooth interpolation.

1 Introduction

Over the past decade computer assisted surgery has evolved from early laboratory experiments to clinical prototypes and industrial products. The main idea is to provide the surgeon a broad spectrum of information about the anatomy and physiology of the patient during interventions. One possible solution is to spatially align the pre-operative images with intra-operative acquisitions.

The main objective of this research[1] is to create a framework allowing to piecewise rigidly register pre-operative spine images with intra-operative data reflecting the actual state of the patient's anatomy during intervention.

Conventional registration methods as described in the review article [1] will fail when registering spine data. The reason lying in the interleaved nature of the spine consisting of the rigid vertebrae and surrounding soft tissue. It is therefore important, that prior to registration each vertebra is separated from its neighbors and treated as a rigid body during registration. While many different methods have been proposed for medical image segmentation (see [2] and the references therein), literature is sparse in the field of vertebrae segmentation and registration. The most promising approach so far are the deformable models and their improved extensions using a priori knowledge in the form of parametric or statistical models [3,4,5].

2 Methods

Piecewise rigid registration is a two-stage process. In the first stage, the vertebrae of the spinal column to be registered are extracted. In the second step, all the segments are registered using prior knowledge of spatial relations between them.

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Vertebra Segmentation: A spinal column consists of vertebrae interleaved with soft tissues such as intervertebral discs. It follows an S-shaped curve and allows for a certain degree of flexibility in bending and twisting. As the main shape features of the vertebra are oriented either parallel or perpendicular to the centerline of the spinal canal, the extraction of this centerline is the logical first step of the segmentation process.

As the spinal canal is a tubular structure located inside the spinal column, we can assume a simplified model: a cylindrical structure with longitudinal orientation enclosed by bone. In a first step, bones are segmented by thresholding at 200 Hounsfield units (HU). Our simplified model ignores the existence of intervertebral discs and other gaps between bones. To overcome this limitation, a morphological dilation with an ellipsoid structural element (isotropic in axial slice, extended in longitudinal direction) is used to enclose the spinal canal.

Ideally, the spinal canal would be a single tubular structure, practically it consists of several segments (e. g. gaps due to imperfect bridging of intervertebral discs). To extract these segments, connected component labeling of the background enclosed by bone is performed in each axial slice. In some cases the labeling delivers components other than the spinal cord e. g. inside the vertebral body or areas falsely enclosed by the dilation. Unsuitable components are discarded based on the size and shape of the 2D components and 3D segments they create. The spinal cord approximation is iteratively constructed from the remaining segments, starting with the largest. Conflicts (more than one segment in a slice) are resolved in favor of the continuity of the already constructed part. For each slice intersecting the spinal cord approximation, a mass center of the intersection marks a rough centerline position. The final centerline is a smoothed approximation of such points.

Before we approach the next step of the segmentation process, the volume is straightened by resampling in a way, that each slice is perpendicular to the centerline of the spinal canal. A single threshold segmentation of the reformated volume, as used above, would fail to include the low density bone in the interior of the vertebrae. Therefore we segment the bone, utilizing an automatic technique developed previously [6]. The method adaptively varies the threshold based upon mean and standard deviation of the gray values in the local neighborhood. The adaptive nature causes foreground pixels to occur not only in the bony regions, but also in the soft tissues all around the volume. Therefore we make use of an additional threshold that helps to distinguish the dense bone contours from soft tissues. The gaps in the bone contours, caused sometimes by the operation are, corrected by a 2D morphological closing, followed by the filling of the bone interior.

The last step of the segmentation process is the separation of the vertebrae, Fig. 1(a). The separation surface consists of three parts. The first is a half-plane separating vertebral bodies at the position of an intervertebral disc. The second part is a triangular surface spanning a 90° fan from the spinal cord centerline in the posterior direction. It is positioned in the gap between the laminas and spinous processes of two neighboring vertebrae. The separation is finalized by spanning a ruled surface between boundaries of the half-plane and the fan.

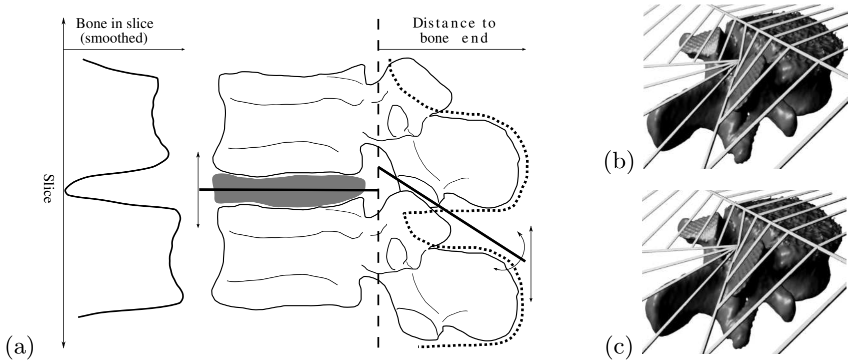
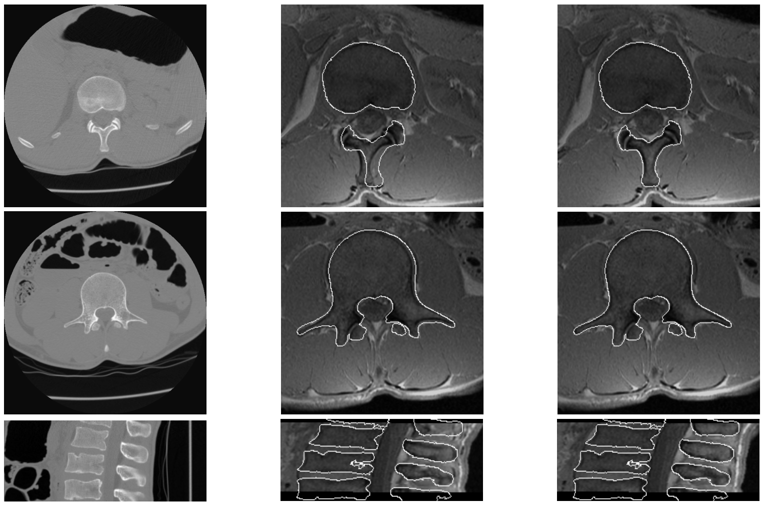


Fig. 1. Segmentation process. (a) Left: The amount of bone voxels in the anterior area of the slice. Regions around the minima coincide with the intervertebral discs. Right: Two consecutive vertebrae in the straightened spinal column overlayed by the scheme of the separation surface construction. Dotted line represents the distance between the spinal canal centerline and the ridge of the lamina or spinous processes. Minimum areas coincide with the posterior gaps between the vertebrae. The tilt is optimized to avoid intersecting the bones. (b) Segmented vertebra and the separation surface. (c) Spinal canal centerline is interpolated in the region of the injured spine.

Non-rigid Registration: The choice of the registration procedure is imposed by both the physical characteristics of the spine and the multi-modal nature of the images. A piecewise rigid strategy seems to be the most suitable approach to accurately model the deformation of the spine structure. This approach allows to decompose the global non-rigid matching problem of the spine into numerous local rigid registrations of the individual vertebrae. The parameters obtained after these local rigid matches are then embodied into a dense global non-rigid deformation field built such that it preserves the rigid characteristics of the vertebrae and elastically deforms the soft tissue around it.

Introduced in 1995 by [7] and [8], mutual information (MI) is seen as the best similarity measure for matching multi-modal images. However, care must be taken to avoid problems with interpolation artifacts [9] and the inherent limitations of MI with images of low structural content [10]. In the context of piecewise rigid spine registration this is of particular importance, as the number of image samples around the rigid vertebrae is relatively small, and the vertebrae are of low contrast in the MR scans. We therefore propose to use a slightly dilated mask, i.e. $2-3$ mm, of the vertebrae, as the regions for the local rigid registration. The extra layer of soft tissue around each vertebrae will not affect the rigid matching, as the deformation is minimal in the proximity of the bone. It will on the other hand increase the reliability of the MI estimation and therefore increase the robustness of the registrations.

Once all the corresponding vertebrae pairs are properly registered, the individual transformations are merged into a global dense deformation field. Using a 3D extension of the technique described by Little et al. in [11] the final deformation field is built such, that it rigidly transforms the vertebrae and elastically deforms the soft tissue around them.



(a) (b) (c)

Fig. 2. Result of a CT-MR spine registration. (a) Transversal and sagittal sections in the reference CT image. (b) The contours of the CT vertebrae overlaid on the corresponding sections in the floating MR image after the global rigid registration. (c) The contours of the CT vertebrae overlaid on the resulting MR sections after the piecewise registration procedure

3 Results

We have tested the segmentation algorithm on 10 datasets containing regions of the cervical, thoracic, lumbal and sacral spine. Two datasets contained vertebrae with missing lamina and spinous processes and three more contained vertebrae with deformations. Since only three of our CT datasets were accompanied with correspondig MRI volumes, the feasibility of the full segmentation and the piecewise registration process was verified on these three cadaver studies.

The spinal canal extraction has proven robust against cases when lamina and spinous processes are missing on some vertebrae. In such cases, the centerline is interpolated from the neighboring vertebrae, Fig. 1(c). The centerline extraction can follow a wrong path in the area of the sacrum, where false canals between the sacrum and pelvis are created by the morphological dilation.

The separation of the vertebrae works robustly in areas of the thoracic and lumbal spine, but often fails in the area of the cervical spine. In one case the last lumbal vertebra was not separated due to incorrect spinal canal centerline detection in the sacrum region. The approach chosen for separating neighboring vertebrae does always not offer proper segmentation of the articular processes. In the cervical area, a purely planar surface might be insufficient to separate the spinous processes. However, even in such cases the fraction of incorrectly separated bone is small and therefore the registration is able to correct for them and give robust results.

The registration algorithm was tested on segmented CT spine data with their corresponding MR scans. Figure 2 depicts a registration result of one of the CT-MR data sets of the spine, showing the contours of the CT segmented vertebra overlaid on the corresponding MR image. The middle column, depicting the result after the global rigid registration, shows the necessity for individual vertebra matching in order to compensate their rotation around the spinal cord. The images from the right column show the result after piecewise rigid registration.

4 Discussion and Conclusions

In this paper we presented an efficient vertebrae segmentation algorithm for CT data. The algorithm provides the centerline of the spinal canal and even if some of the vertebrae are damaged, it is capable to robustly produce results accurate enough to perform reliable piecewise registration of the spine.

We also presented an algorithm for achieving piecewise multimodal registration of the spine. The registration method we presented is not restricted to the CT-MR modalities, but can be used for any other mono/multi-modal image registrations, provided that at least in one of the images the vertebrae can be segmented to define the rigid objects. This piecewise strategy can be suitable for other non-rigid registration applications, if elastic deformations close to or in between the previously defined rigid objects are only of interest.

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