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Vertebral body segmentation with prior shape constraints for accurate BMD measurements

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ABSTRACT

We propose a novel vertebral body segmentation approach, which is based on the graph cuts technique with shape constraints. The proposed approach depends on both image appearance and shape information. Shape information is gathered from a set of training shapes. Then we estimate the shape variations using a new distance probabilistic model which approximates the marginal densities of the vertebral body and its background in the variability region using a Poisson distribution refined by positive and negative Gaussian components. To segment a vertebral body, we align its 3D shape with the training 3D shape so we can use the distance probabilistic model. Then its gray level is approximated with a Linear Combination of Gaussians (LCG) with sign-alternate components. The spatial interaction between the neighboring voxels is identified using a new analytical approach. Finally, we formulate an energy function using both appearance models and shape constraints. This function is globally minimized using s/t graph cuts to get the optimal segmentation. Experimental results show that the proposed technique gives promising results compared to other alternatives. Applications on Bone Mineral Density (BMD) measurements of vertebral body are given to illustrate the accuracy of the proposed segmentation approach.

1. Introduction

Osteoporosis is a bone disease characterized by a reduction in bone mass, resulting in an increased risk of fractures. To diagnose the osteoporosis accurately, Bone Mineral Density (BMD) measurements and Fracture Analysis (FA) of vertebral bodies are required. The spine bone consists of vertebral body and processes as shown in Fig. 1, however, spinal BMD measurements and Fracture Analysis are restricted to the vertebral bodies. Our main objective is the segmentation of vertebral bodies from computed tomography (CT) images to be used in BMD measurements and fracture analysis.

Actually, isolating a vertebral body (VB) form its background is not an easy task due to challenges in spinal CT images as shown in Fig. 2. These include inner boundaries, osteophytes, bone degenerative disease, double boundary, and weak edges of spine bones. Also, exposure levels, slice thickness, and volume of interest affect the resolution of CT images. Due to these challenges appearance-based segmentation techniques prone to fail in such cases because of noise and region inhomogeneities. Fortunately, organs have well-constrained forms within a family of shapes [1]. These prior knowledge of shapes and other properties of the structures are exploited in organ's segmentation e.g., deformable model combining shape knowledge [2] and minimizing an Euclidean distance between a given point and its shape prior [3]. Therefore; the proposed framework tries to overcome these inhomogeneities and accurately segment VBs using shape and appearance information.

A huge number of approaches for segmentation of vertebrae and vertebral structures were proposed in the literature: Simple techniques such as thresholding and region growing (e.g. [4,5]), parametric deformable models (e.g., [6]) and geometrical deformable models (e.g., [7,8]). Kang et al. [4] proposed a 3D segmentation method for skeletal structures from CT data. Their method is a multi-step method that starts with a three dimensional region growing step using local adaptive thresholds followed by a closing of boundary discontinuities and then an anatomically-oriented boundary adjustment. Applications of this method to various anatomical bony structures are presented and the segmentation accuracy was determined using the European Spine Phantom (ESP) [9]. However, similar to other appearance-based approaches, this method can not overcome gray level inhomogeneities, and diffused boundaries.

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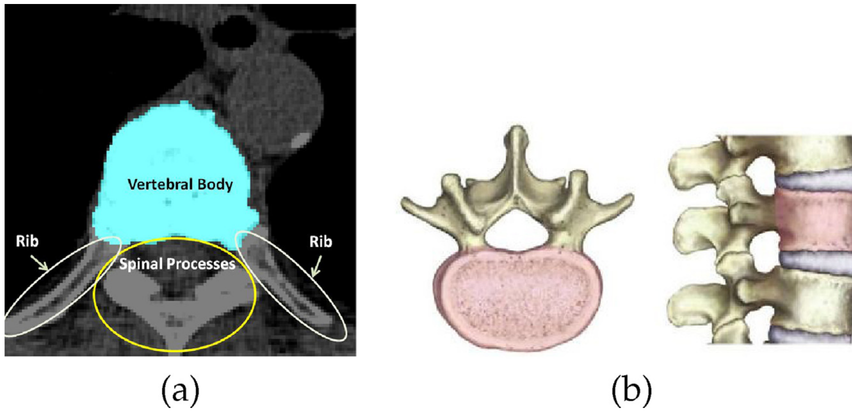

Fig. 1. Vertebral body: (a) A CT slice of vertebral body illustrates its regions: the VB region (in blue color), which is our region of interest to be segmented. Spinal processes and ribs, which should not be included in the BMD measurements, are shown as well. (b) Axial and Sagittal views of vertebral body. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

Mastmeyer et al. [7] presented a hierarchical segmentation approach, which combines deformable model and geometrical shape knowledge, for the lumbar spine in order to measure BMD. They reported that their algorithm can be used to analyze three vertebrae in less than 10 min. This timing is far from the real time required for clinical applications but it is a huge improvement compared to the timing of 1–2 h reported in [10].

Many statistical approaches, which are used in the 3D modeling of structures, are based on shape analysis. Active appearance models [11] and active shape models [12] are successfully used to recover object geometries from set of points. For instance, Robert et al. [13] used the active appearance model to analyze the fracture of vertebral bodies. An alternative formulation to address model-based segmentation is implicit representations e.g., [14,15]. Farag and Hassan [15] proposed a statistical level set framework. The segmentation process starts by initializing the level set function as the signed distance function of a circle entered at seed point(s) that can be either manually placed by the user or automatically selected. Then, the intensity probability density within an object and background is modeled using a Gaussian probability distribution whose statistical parameters are adaptively updated during the course of evolution of the level set function. However, such model-based segmentation techniques suffer from fitting errors when no clear object boundary is visible e.g., in presence of pathologies. Klinder et al. [16] developed an automated model-based vertebra detection, identification and segmentation approach. This approach combines a statistical modeling of intervertebral transformations with gradient-based appearance. However, this optimization technique prone to nonlinearity and local minimums.

Recently, Ma et al. [8] presented a sophisticated approach to segment and identify the thoracic vertebrae in 3D CT images. They learned 12 statistical shape models of thoracic vertebrae, to be used in a coarse-to-fine, two-stage segmentation strategy: a group-wise deformation of 12 vertebra subregions is followed by deformations of smaller neighborhoods of vertebra mesh vertices. The deformable model is derived by learned vertebra edge candidates using steerable features. This approach can be used to segment VB if only VB's subregions are used in the coarse-to-fine deformation stage or by using a post-processing step to split VB's surface from processes surface. However, segmenting VB using this method is very sophisticated than what we propose. First we use only a global shape model instead of 12 statistical shape models used in former method. Second, in our approach, shape is globally aligned then VB is segmented by minimizing a cost function. Where, in Ma et al. [8] approach, 12 shape models should be deformed by minimizing a cost function after that small batches are deformed by minimizing another cost function. Moreover, additional processes removal step is needed.

Most of the previous works construct a shape model for each vertebrae type or construct a single shape model and deforming it to fit each vertebrae type, which needs a strong boundary. Unlike these approaches, we construct a general shape model for VB. The proposed shape model acquires the geometric variability of VBs' types. In this paper, we propose a MAP-based segmentation approach that uses graph cuts to combine region and boundary properties of segments as well as shape constraints. Image modeling, in this work, is a unified approach, which is created by integrating several of our previous and ongoing efforts in image modeling techniques. First, we model the shape variations using our new distance probabilistic model [17]. This distance model approximates the distance marginal densities of the VB and its background inside the variability region using a Poisson distribution refined by positive and negative Gaussian components. For each given VB set of images, to use the distance probabilistic model, we align the given 3D shape with the training 3D shape. Then VB's gray level is approximated using our linear combination of

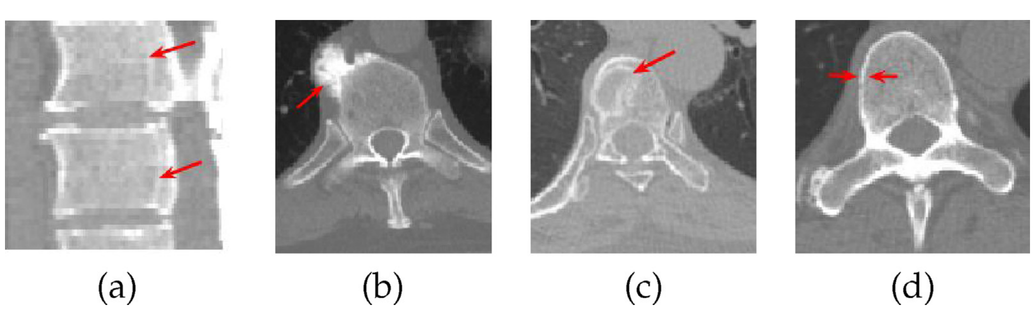

Fig. 2. Typical challenges for vertebrae segmentation. (a) Inner boundaries. (b) Osteophytes. (c) Bone degenerative disease. (d) Double boundary.