Segmentation of Intervertebral Disc Space in 3D CT Images

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Abstract

The problem of automatic 3D segmentation of vertebral discs in CT datasets is considered. The difficulty with the vertebral disc is that, opposite to MRI, it has low contrast in CT and is usually indistinguishable from the surrounding soft tissue. On the other hand, parameters measured in this volume of interest (VOI) may be of interest as additional fracture risk predictors for osteoporotic patients. Also, finite element analysis of the vertebral column can be done more accurately when vertebral discs are included.

Two segmented VOIs are created between each pair of vertebrae: a core VOI (approximates nucleus pulposus) and an extended one (corresponds to annulus fibrosus) which have different structural and material properties. The definition of segmented disc volumes is based on the shape of two neighbouring vertebrae only and allows for simple and robust implementation which was validated in a set of CT images of whole spine of a cadaver study including 27 patients with 135 analysable discs. As a side effect of the segmentation method, simple detection of vertebral endplates is possible.

1 Introduction

Osteoporosis is a bone disease characterized by low bone mass and microstructural deterioration leading to an increased risk of fracture. Its most severe outcome is hip fracture which is associated with a 20% mortality in the first year after fracture [3]. Heavy economical burden associated with the treatment of the severe consequences of fractures stimulates research aimed at the prevention of osteoporosis, which is primarily a disease of the elderly population.

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Main locations used to diagnose osteoporosis are the spine and the proximal femur. Dual X-ray absorptiometry (DXA) is the standard imaging modality to measure bone mineral density at these sites. As DXA is a projectional technique, only an areal bone mineral density (aBMD) can be obtained. Nevertheless, aBMD is a predictor for further fractures. However, the additional dimension in the volumetric bone density as measured in quantitative CT (QCT) allows for more detailed analysis of density distribution in bones and in the spine shows better fracture prediction [5].

Another potential advantage of QCT is the availability of 3D bone geometry. Osteoporotic fracture associated changes in vertebral shape can be clearly seen even in 2D. So far in the field of osteoporosis one aspect of the volumetric vertebral geometry is unaddressed, however: the shape of vertebral discs. The discs are known to undergo significant deformations in osteoporotic patients [1]. Unfortunately, they are 'invisible' in QCT: one cannot distinguish the discs from the surrounding soft tissue (see Figure 1 a&b). What one can do instead is to define an intervertebral disc space (IDS) which coincides approximately with the disc itself. One such definition is proposed here and is used to segment the core and extended IDS volumes of interest (VOI) which are supposed to approximate the nucleus pulposus and annulus fibrosus of the vertebral disc, respectively.

From the medical application point of view, distinguishing between these two compartments may be necessary for building realistic finite element models of the vertebral column since they possess different mechanical properties. We will call the union of core and extended IDS the complete IDS or just IDS in the remaining text.

Summarizing, the purpose of the paper is to develop an algorithm for robust automatic segmentation of IDS in 3D CT images of lumbar and thoracic spine.

2 Materials and Methods

2.1 QCT Datasets

27 human cadavers aged 65-90 were used for the study. All acquisitions were made on a Philips MX8000 scanner with the following parameters: 120kV, 100 mAs, slice thickness 1.3 mm, field of view 15–16 cm. Scan ranged included vertebrae from T6 to L4 with adjacent endplates of T5 and L5. The majority of patients had osteoporosis and a few of fractured vertebrae. Fractured or other severely degenerated vertebrae were not used in the analysis so that adjacent IDS were not segmented as well (see Figure 1 (c)).

2.2 Segmentation method

As a prerequisite for IDS segmentation, the vertebral bodies superior and inferior to each disc must be segmented. This was done using the semi-automatic segmentation and analysis approach of [2], implemented in the Medical Image Analysis Framework (MIAF), application MIAF-Spine, which also provides a segmentation of the inner, trabecular VOI. See Figure 1 (c) for an example of the segmented vertebral column.

We define IDS in CT images as a part of an image space bounded by two adjacent vertebrae and a 'lateral' surface connecting their most proximate points. The exact meaning of the definition will become clear from single steps detailed below.

First, we use the trabecular (inner) VOIs of two adjacent vertebrae to find the core IDS part. For this we apply morphological closing to these VOIs with a spherical structuring

(a) (b) (c)

Figure 1: (a and b): Illustration of the different appearance of vertebral discs in two modalities: a CT slice on the left and MR one in the centre. One can clearly distinguish the borders of individual discs in MR, but in CT the discs are indistinguishable from surrounding soft tissue. (c): Example of a whole spine scan with segmentation of unfractured vertebrae (outer, periosteal volumes in red; inner, trabecular compartment in blue).

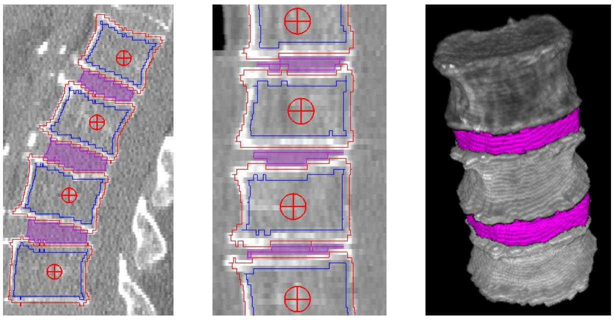

Figure 2: Example of core IDS segmentation on (left to right): sagittal slice of a lumbar vertebral compartment, sagittal slice of a thoracic compartment, 3D view of T12–L2.

element of large radius (10 mm), so that the two trabecular VOIs and a part of the space between them unite into one segment. The core IDS is then obtained by subtracting (in the sense of set theory) periosteal (outer) segmentation masks of the two vertebrae from the obtained segment. Using outer segments as protective masks removes all voxels from the lateral surface of the trabecular compartments and limits the result to the space between the endplates. See Figure 2 for an example of core IDS.

The second step of the segmentation algorithm expands the core VOI into the complete IDS according to our definition. To find the lateral surface of the complete IDS we search shortest lines connecting two adjacent vertebral bodies. However, the distance between anterior and posterior parts of the two vertebral bodies may significantly vary due to the curvature of the vertebral column. That is why we search the shortest line segment in separate sectors dividing the cylinder V that encompasses the IDS (see Figure 3). Each such line possesses the obvious property: the sum of distances to the vertebral bodies for each point on the line is equal to the line length, which is minimal by definition. This simple observation gives us practical way to finding the shortest lines.

For this we compute two distance maps, for each of the two vertebral bodies, i.e., in every voxel of a cylinder V we compute the shortest distance to the first and to the second

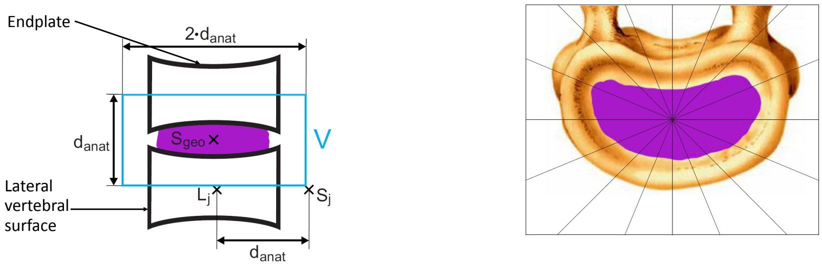

Figure 3: Left: schematic representation of the cylinder V surrounding the IDS; right: its partitioning into sectors. The radius and the height of V is equal to the distance from the centre of mass of the underlying vertebra L_j to the corresponding point in the spinal canal S_j, which is automatically computed in MIAF-Spine for the whole vertebrae after user sets one seed point in the canal [2]. This adaptation of the size of V on the size of the vertebra is done solely with the purpose to minimize the run-time. Using a cylinder of the large fixed radius would produce identical results.

vertebra. For simplicity let us assume that the distance maps are continuous. In every sector we look for points with the smallest sum of values from the two distance maps. Collecting such lines in every sector we build a 'fence' around the core IDS. The lines are locally (in the corresponding sector) shortest lines connecting the two vertebrae. There were 72 sectors used in our implementation, with the angle of 5° for each sector. In the discrete case, we search points having the minimal sum of two distances plus a certain small number, half of the voxel dimension.

The final step that remains to obtain the complete IDS is to apply morphological closing to the 'fence' and core IDS in order to fill in the 'holes in the fence'. The optimal radius of the structuring element can be easily found as the maximal distance between two points from two adjacent sectors of the cylinder V: structuring element must fit the maximal possible 'hole in the fence'.

Finally, with the segmentation of two vertebral bodies and IDS in between we immediately get the surface of the endplates. Namely, the endplate of a vertebra contains all its surface points that neighbour the adjacent IDS or vertebral body (because sometimes there is no gap between two vertebrae).

3 Results

We have tested the proposed segmentation method in 27 QCT spine datasets with a total of 180 unfractured vertebrae and 135 analysable IDS. Segmentation of all 135 IDS was successful which means that all segmentations conformed to the above stated definition of IDS. The segmentation runs completely automatically. It requires segmented vertebral bodies as input which are provided by the semi-automatic approach implemented in MIAF. See Figure 4 for an example of IDS segmentation and Figure 5 for an illustration of segmented endplates. These results were evaluated by an expert reader who has found them accurate in all cases except for 5 IDS where the segmented volumes were a little bit too small. A segmented IDS was considered accurate if it occupied exactly the space between edges of the endplates. Presence of osteophytes near the edges in those 5 IDS made them boundary points of the IDS so that the true IDS size was underestimated.

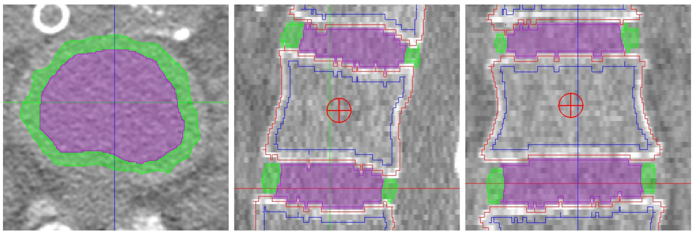

Figure 4: Example of IDS segmentation in three multiplanar reformation slices: axial, sagittal, and coronal. Core IDS and surrounding extended IDS volumes are shown in purple and green, respectively.

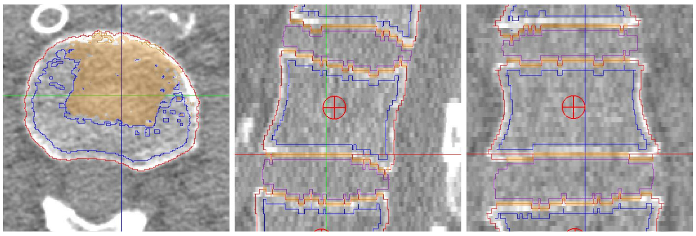

Figure 5: Example of segmentation endplates in three multiplanar reformation slices: axial, sagittal, and coronal. Additionally to endplates, the periosteal, trabecular, and IDS bounding surfaces are shown.

4 Discussion

In the current manuscript, we have developed a new automated and robust segmentation of the intervertebral disc space in CT. The first results showed, at least qualitatively, the suitability of the method. Sometimes, our definition seems to underestimate the width of the vertebral discs due to specific variations of the shape of endplates. However, the core IDS segmentation is independent of endplates and its size is very close to that of the whole IDS volume so that produced error is limited to a small range. Also importantly, the segmentation of endplates is readily available from IDS segmentations, an otherwise complex segmentation problem. Of course, the quantitative estimation of the accuracy shall be done next. For this, a spine phantom like European Spine Phantom can probably be used. A more realistic approach would involve segmentation of vertebral discs in MR images of the same patients and their comparison with results from CT, although it is not obvious how to compare vertebral discs with IDS which are different objects. Next, inter-operator precision will be established. Note however, that the segmentation of IDS itself is completely automatic and depends on segmentation of adjacent vertebral bodies only, which is known to be rather independent from the operator. Specifically, the proposed algorithm is essentially independent of any parameters. There are few internal parameters; however, they may be significantly varied without affecting the results. Thus, the size of the structuring element for core IDS is chosen to fit the largest possible IDS height. Larger elements produce almost the same results at the price of the higher computational costs though. Similarly, number of sectors in the partitioning of the cylinder for the extended IDS was chosen large enough to have fine-grained lateral IDS surface so that increasing the number even further would make only minimal changes (less than the sector width). Summarizing, the accuracy of the algorithm cannot be easily quantified; but the precision error is kept minimal which is often more important, e.g., in longitudinal studies.

Our simple definition of the 'lateral' surface of the complete IDS is based on the observation that endplates of vertebrae are always concave so that distance between points on the ridges of two adjacent endplates is shorter than distance between any two points locating on the inner part of the endplates, even though the endplates may lie with an appreciable angle due to curvature of the vertebral column.

To the best of our knowledge no publications exist for the problem of automatic vertebral disc segmentation in CT, at least in the clinical context of osteoporosis. There are few articles, however, which deal with the estimation of the height of intervertebral disc spaces. One example is [4], the approach implemented therein can be modified to obtain the segmentation of IDS too. The computation of IDS height in [4] is based on the segmentation of endplates using a level-set approach: a level-set contour grows from a seed point on an endplate of the segmented vertebral body with the velocity diminishing on points with high curvedness. Effectively, it would stop on the 'ridgeline' unless stopped before by pathological structures. In contrast, our proposed method normally connects the two ridgelines of neighbouring vertebrae leading to essentially the same results but with a simpler technique. Moreover, segmentation of the core IDS ensures that the results are not affected by any surface irregularities in the middle of the endplates.

The developed segmentation algorithm will be augmented by the calculation of geometrical parameters of IDS and endplates. These parameters will in turn be assessed for their contribution into the fracture risk prediction: whether they can enhance the standard prediction statistics involving vertebral BMD. Another planned application is the finite element analysis of a range of the vertebral column using segmentation and material properties of vertebral bodies and vertebral discs.

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