Novel usages of distance function in fully automatic articular cartilage segmentation

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Introduction: Accurate segmentation of articular cartilage is important for MRI-based diagnosis and therapy of cartilage diseases, e.g., osteoarthritis. Fully automatic segmentation is desired since it is both time- and cost-efficient. Unfortunately, automatic segmentation of articular cartilage is challenging because 1) signal contrast between cartilages and surrounding soft tissues is poor; 2) cartilages contact each other and no obvious contrast exists in the contact interface. To overcome these difficulties, shape-model based regularization is used in current automatic cartilage segmentation techniques [1, 2]. However, this method requires the user input of pre-defined shape model, and may provide incorrect regularization for worn cartilage. In this study, we propose to use distance function to attack these difficulties in cartilage segmentation with segmented bone instead of prior shape information of cartilage. Distance function of an object is defined as the smallest distance from a point in the domain to the object. Given segmented bones, distance function of these bones can be calculated [3]. In this work, new application of distance function is proposed to: 1) reduce the search region of cartilages; 2) segment cartilages based on the smoothness of cartilage thickness when there is no contrast between cartilages and surrounding soft tissues; 3) separate contacted cartilages when there is no obvious contrast between them; 4) provide thickness map for cartilages. The proposed method was tested on twelve MRI data sets.

Method**:** Compared to cartilage, bone can be segmented with less difficulty**.** Given a segmented bone, the distance function of the bone can be calculated. Fig. 1a shows an example of distance function of a femoral bone. Using the directional gradient [1], the bone cartilage interface (BCI) can also be found. (1) Reducing the search region of cartilages: If the upper bound of the cartilage thickness can be estimated, a narrow band can be defined using the distance function. A point in this narrow band has a distance to the BCI smaller than the upper bound. Since cartilage is attached to bone, it is only necessary to search the cartilage in this narrow band. Hence, the time for segmentation can be reduced. Fig. 1b shows an example of the narrow band. The yellow line is the BCI of femoral bone, the region between red lines and BCI is the searching region; (2) Segmentation based on the smoothness of cartilage thickness when no contrast is available: Boundary of one side of cartilage is defined by BCI. Let cartilage surface (CS) be the boundary of the other side of cartilage. Once a potential CS is given, the cartilage thickness along CS can be easily checked using the distance function. Fig. 1c shows an example of CS and their corresponding closest points on BCI in the image. Fig. 1d plots the cartilage thickness along the CS. It can be seen that the thickness changes gradually and there is no very big jump. Hence, the smoothness of thickness can be used for segmentation when there is no contrast. For a given point on BCI, the cartilage thickness at this point can be approximated by its neighbor's thickness using smoothness criteria. The corresponding point on CS for that given point on BCI can be found using the thickness. It should be noted that this segmentation scheme is only used for regions where the contrast is not sufficient for segmentation on the cartilage surface. Hence if sufficient contrast is provided to describe CS, big jump in cartilage thickness can be detected; (3) Separation of attached cartilages: If there is no contrast between two contacted cartilages, segmentation based on thickness smoothness is first applied. However, it is possible that there are still overlaps of these two cartilages. A simple, but maybe not accurate, approach is to divide the intersection based on distance. For a point in the intersection, the distance to each bone can be found using the distance function. This point is assigned to the nearer bone; (4) Automatic generation of cartilage thickness map: An important quantitative property of cartilage is thickness. Euclidean distance transformation (EDT) has been proposed for accurate cartilage thickness calculation [4]. EDT is one example of a simple implementation for calculation of distance function. The calculation using closest point [3] is more sophisticated and fast. With the calculated distance function, the thickness of any point on CS is automatically provided by the distance function.

Results: 3D knee MRI images were acquired on a Philips Achieva system using water saturated fast field echo (FFE wats) sequence. Both left and right knee data sets with a size of either 320×320×170 or 512×512×64 were acquired from 6 patients. Bones were segmented using an in-house fully automatic segmentation algorithm, and corresponding BCIs were found using directional gradient. 2D distance functions were calculated according to Ref [3] slice by slice with the segmented bone. Narrow bands were defined with the calculated distance function. Gradient was used to search the CS in the narrow bands. When there was no sufficient contrast, *i.e.*, very low gradient, distance function was used for segmentation as described above. At last, distance function was applied to divide contacted cartilages. In addition, cartilage thickness was directly indexed from the distance function. Some segmentation results are shown in Figure 2 (Figs. 2a~c: right knee; Figs. 2d~f: left knee). It can be seen from Figs. 2a and 2d that there are no overlaps between cartilages even though there are no sufficient contrast between them. The white arrows in Figs. 2a and 2b shows the segmentation using thickness smoothness when there is no sufficient contrast between cartilage and surrounding soft tissue. Figs. 2b and 2e demonstrate the corresponding thickness maps. Figs. 2c and 2f are the 3D visualization of the segmentation. Each color demonstrates one kind of cartilage.

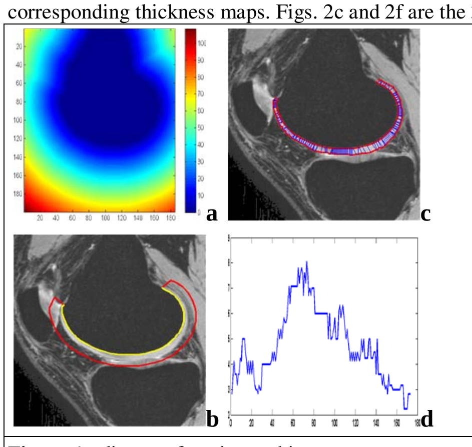

Figure 1. distance function and its usages

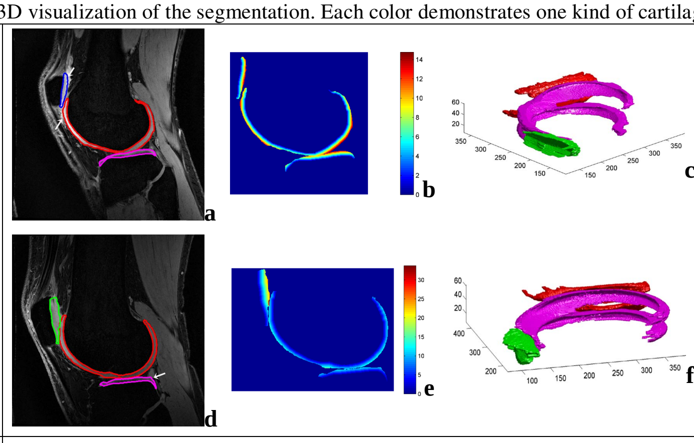

Figure 2. Segmentation results of a right (top row) and a left (bottom) knee

Reference**:**

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Discussion and Conclusion: In this work, new applications of distance functions are proposed for cartilage segmentation and cartilage thickness calculation. Using the distance function, regions where there is no sufficient contrast can be segmented and searching region for cartilage can be narrowed down. In our experiments, the distance function was used together with a simple edge-based segmentation method. With the help of distance function, difficulties encountered by edge-based segmentation method, such as segmenting low contrat regions, were avoided and accurate segmentation was obtained for all data sets. The distance function can also be used with other segmentation techniques, either 2D or 3D. If prior shape information is availabe, more accurate results may be obtained with the help of distance function. In conclusion, distance function can be efficiently applied to cartilage segmentation at regions where there is no sufficient contrast, and the calculation of cartilage thickness. It can also effectively reduce cartilage searching region.