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Semi-automatic segmentation of femur based on harmonic barrier

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ABSTRACT

Background and Objective: Segmentation of the femur from the hip joint in computed tomography (CT) is an important preliminary step in hip surgery planning and simulation. However, this is a time-consuming and challenging task due to the weak boundary, the varying topology of the hip joint, and the extremely narrow or blurred space between the femoral head and the acetabulum. To address these problems, this study proposed a semi-automatic segmentation framework based on harmonic fields for accurate segmentation.

Methods: The proposed method comprises three steps. First, with high-level information provided by the user, shape information provided by neighboring slices as well as the statistical information in the mask, a region selection method is proposed to effectively locate joint space for the harmonic field. Second, incorporated with an improved gradient, the harmonic field is used to adaptively extract a curve as the barrier that separates the femoral head from the acetabulum accurately. Third, a divide and conquer segmentation strategy based on the harmonic barrier is used to combine the femoral head part and body part as the final segmentation result.

Results: We have tested 40 hips with considerately narrow or disappeared joint spaces. The experimental results are evaluated based on Jaccard, Dice, directional cut discrepancy (DCD) and receiver operating characteristic (ROC), and we achieve the higher Jaccard of 84.02%, Dice of 85.96%, area under curve (AUC) of 89.3%, and the lower error with DCD of 0.52mm. The effective ratio of our method is 79.1% even for cases with severe malformation. The results show that our method performs best in terms of effectiveness and accuracy on the whole data set.

Conclusions: The proposed method is efficient to segment femurs with narrow joint space. The accurate segmentation results can assist the physicians for osteoarthritis diagnosis in future.

1. Introduction

As one of the most important joints in human body, hip joints often suffer from frequent postnatal wearing, accidental impact and functional degradation, which may result in common pain and bone deformities. To diagnose these complicated symptoms before clinical treatment, segmentation of a pelvic CT scan offers accurate and compact representations of patient-specific hip bones [1]. Furthermore, it is also an important prerequisite of surgical planning, cinematic analysis of joints and navigation for total hip replacement [2].

The accurate femur segmentation with less interaction is a challenging task. Specifically, the hip joint is a unique and complex structure with a ball-resembling femoral head and socket-resembling acetabulum [3], the joint space between the femoral head and the acetabulum is very narrow, and it consists of soft tissues such as cartilage and ligaments [4]. In some cases, due to malformation and noise, the narrow space becomes more obscure and even disappears in some regions, which makes detecting boundaries of those two closely related tissues more difficult. Furthermore, the integrated femur contains not only the femoral head but also the greater and lesser trochanter. These anatomical characteristics make the corresponding topology of femur change in different CT slices, e.g. the femur may appear as two unconnected regions in some slices, but as one region in others.

Many methods have been proposed to segment objective tissues from CT images, which can be classified into two categories. The methods in the first category are referred to as slice-based

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methods, since they treat the input CT data as a sequence of 2D slices, which are their original forms. For example, Liu et al. [3] use a hybrid segmentation frame with a complex combination of low-level image analysis techniques such as thresholding and region growing from coarse to fine, but it cannot guarantee the right region of the femur in each slice and sometimes fails to avoid the shrinking and leaking problems in areas where the foreground and background have similar intensity distributions. As pre-processes, valley emphasis and Bayes decision rules can be adopted to enhance the contrast of edges in slices [3,5]. To deal with the problem of topology changes, Gabriel et al. [6] divide the volume into two parts manually, and use an active contour-based method (i.e. the Snakes) to get the contour of the femur in each slice after removal of the acetabulum. The effort of Snakes could act rather well to acquire object contours on the assumption that the acetabulum part is removed completely from each slices, however, such an assumption is hard to achieve. With the aid of shape information, an ellipsoid [7] or a quadric ellipsoid [3] shape is used to fit the femoral head as its rough contour, but such an approximation is often inappropriate for a deformed hip joint and is hard to correct on account of the large fitting error in some slices.

The methods in the second category are referred to as volume-based methods. They treat the input CT data as a 3D entirety (i.e. volume data). As a robust method, the Statistical Shape Model (SSM) [8] has been widely used in segmentation and uses a statistical shape as prior information, however, it relies heavily on a proper shape model for initialization. Moreover, the construction of 3D shape models is a time-consuming and complex task due to the high variability of femurs. The Active Shape Model (ASM) [9] segmentation also incorporates a priori information. For example, ASM and Graph-cut are adopted by Huang et al. [10] to segment the femur, but it depends mainly on correcting corresponding landmarks between two different objects, which is error prone and subjective because the landmarks are critical for the results and need to be manually chosen with great patience and labor.

In this paper, we aim to develop a new segmentation technique for hips with overcrowded joint space in terms of high accuracy, robustness and less interaction. To solve topology changes of the femur and inspired from the reference [6], we treat the femur as (1) the femoral head part and (2) the femoral body part, and treat them with different segmentation strategies accordingly. Segmenting the femoral head is our primary concern due to the complexity of its structures. To solve the weak boundary problem of the femoral head, our core idea is to adaptively find an optimal iso-line (referred to as barrier in this paper) in the detected joint space region based on harmonic field theory, which can separate the femoral head and acetabulum effectively. As excellent properties of the harmonic field, the candidate barriers identified by the harmonic field are guaranteed to be smooth and will not converge to a local region, which is crucial for the segmentation accuracy (see Section 2.3). The proposed framework is implemented on a slice-by-slice basis, which is more convenient and intuitive for user interactions than locating positions in the perspective view with volume rendering.

The proposed segmentation framework consists of five parts: (1) preprocessing, (2) joint space location, (3) harmonic field construction, (4) barrier identification, and (5) divide-and-conquer strategy based on barrier. Fig. 1 demonstrates the outline of the proposed method. Among these steps, step (3) and (4) are the core steps focusing on constructing a harmonic field with improved gradient and identifying a barrier with ranking for femoral head segmentation, while the result of step (2) offers an optimal ring region according to statistical information obtained from step (1) for reducing the range of harmonic field generation. Step (5) implements the final segmentation in a divide-and-conquer way.

2. Material and methods

Our approach tested 20 pelvic CT scans containing 40 femurs with different complexity categories as introduced in [7]. These data were collected between 2011 and 2015, at the Xiangya Hospital of Central South University from patients needing medical treatment such as total hip replacement. For each data set, the number of slices ranges from 226 to 487, and each of the slices has a resolution of 512 by 512. In volume, the physical spacing of neighboring voxels is $0.65 \times 0.65 \times 1.00$ mm. Different from Ref. [7], our work mainly focuses on more complication CT data with a narrow joint space, and all the data set in our research are divided into three groups according to different levels of difficulty, namely Group A, B, and C. Numbers of hips belonging to Group A, B, and C are 17, 14, and 9, respectively.

Group A: The acetabulum and the femoral head are close to each other, and the joint space is narrow in several slices of each data set. The shape of the femoral head resembles a 3D ellipse. Cortical and spongy bone tissues have higher image intensity than their surrounding tissues. In the first row of Fig. 2, three typical slices are shown.

Group B: The acetabulum and the femoral head are adjacent physically, and the shape of the femoral head is irregular and is different from that of the 3D ellipse. The bone tissues in different parts are not uniformly distributed. In the second row of Fig. 2, three typical slices are shown.

Group C: The joint spaces nearly disappear in some slices or there are breakages in hip bones and the femoral head is irregular due to malformation, lesions, etc. Many holes appear in bones due to very unevenly distributed bone tissues. In the bottom row of Fig. 2, three typical slices are shown.

2.1. Preprocessing

As a common step in the most cited femur segmentation methods, histogram-based thresholding [7] is used in this paper. The result of thresholding is a binary mask, where the bone tissues are supposed to be labeled as foreground, while others are labeled as background. The mask, in this work, serves as (1) statistical data for the joint space identification, which is tolerant of small input variation, and (2) information to segment the femoral body part, which is less challenging. Our method is insensitive to the output of thresholding for two reasons. Firstly, in our study the result of pre-processing is not used for segmenting femoral head but offers a statistical information. In fact, the harmonic field calculation (see Section 2.2.2) responsible for the result accuracy carries out on original CT images. Secondly, refining approaches such as region growing and morphology performed on the mask data are used in this paper for segmenting the femoral body. Without disturbing tissues like acetabulum around such part anatomically, the traditional methods with mask data are competent in solving the segmentation of femoral body generally.

2.2. Joint space location

The reasons for locating join space are two-fold. Firstly, in most cited femur segmentation studies [3,5–7], the shape information of joint space is useful prior knowledge as an important guide for segmentation. Secondly, the location offers an optimal Region of Interest (ROI) for harmonic field generation. We observes that the contour shape for both the femoral head and surrounding acetabulum are approximately circles. Conventional ways of selecting ROI like locating a rectangle region by preset [7] or disk region by Hough transform [6] usually detects an a larger ROI needing more computational cost for harmonic field calculation. Different from those above, we use a ring region determined by two concentric