Estimation of Cartilaginous Region in Noncontrast CT of the Chest
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ABSTRACT

Pectus excavatum is a posterior depression of the sternum and adjacent costal cartilages and is the most common congenital deformity of the anterior chest wall. Its surgical repair can be performed via minimally invasive procedures that involve sternum and cartilage relocation and benefit from adequate surgical planning. In this study, we propose a method to estimate the cartilage regions in thoracic CT scans, which is the first step of statistical modeling of the osseous and cartilaginous structures for the rib cage. The ribs and sternum are first segmented by using interactive region growing and removing the vertebral column with morphological operations. The entire chest wall is also segmented to estimate the skin surface. After the segmentation, surface meshes are generated from the volumetric data and the skeleton of the ribs is extracted using surface contraction method. Then the cartilage surface is approximated via contracting the skin surface to the osseous structure. The ribs’ skeleton is projected to the cartilage surface and the cartilages are estimated using cubic interpolation given the joints with the sternum. The final cartilage regions are formed by the cartilage surface inside the convex hull of the estimated cartilages. The method was validated with the CT scans of two pectus excavatum patients and three healthy subjects. The average distance between the estimated cartilage surface and the ground truth is 2.89 mm. The promising results indicate the effectiveness of cartilage surface estimation using the skin surface.

Keywords: Pectus excavatum, cartilage estimation, skeletonization, surface contraction

1. INTRODUCTION

Pectus excavatum (PE) is the most common major congenital deformity that is characterized by a sternum and costal cartilage depression. It occurs in approximately 1 of every 400 white male births and 1 of every 1000 white female births [1]. PE is more than a cosmetic deformity. Severe deformities can cause cardiopulmonary impairment and reduction in lung volume resulting in easy fatigability, decreased stamina and diminished exercise tolerance. The PE depression most frequently involves the lower end of sternum and cartilages 4 through 7 with varying degrees of rotation and asymmetry. Physical examination, charts, preoperative photographs and computed tomography (CT) scans are used to identify PE cases. The Haller index calculated from CT scans was developed to provide an objective measure of the depth of the deformity for determining surgical eligibility [2].

Surgical repair of PE can be performed via either open operation (Ravitch technique) or minimally invasive procedure (Nuss technique) that involves sternum relocation with or without resection of cartilages. The minimally invasive technique, first described by Nuss et al in 1998 [3], involves the placement of a substernal concave bar, which is passed behind the sternum through the chest and “flipped” into a convex position to elevate the sternum outward. After the surgical procedure, the metal bar is left in place from 24 up to 36 months (forcing the sternum to a new position), after which it is removed from the thorax. The advantages of the Nuss approach include avoiding an anterior chest wall incision, no resection of rib cartilages, and no sternal osteotomy. In the past decade, this procedure has been used worldwide and is currently a first-line approach for pectus excavatum in many centers [4].

Cartilage plays an important role in PE diagnosis and correction. The accurate estimation of cartilages, depicting the cartilaginous structure, is essential for severity analysis of PE. In our study, estimating the chest cartilages will assist to model the entire rib cage, providing critical information for surgical planning. Moreover, the current minimally invasive procedures are based on the experience of the surgeon. The prosthesis is modeled intraoperatively, by manually bending

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the metal bar using a template based on the patient’s thorax morphology. This process is slow, inaccurate and often leaves imperfections on the surface of the prosthesis. However, cartilage estimation in nonconstrast CT scans is an unexplored topic and a challenging task, due to the poor contrast between cartilage and muscle in the chest (shown in Figure 1).

Figure 1 Noncontrast thoracic CT scans: (a) axial view, (b) coronal view and (c) sagittal view. The ribs and sternum are clearly shown, while the cartilages are hardly visible in noncontrast CT.

The segmentation of cartilages/cartilaginous region was only investigated in contrast CT [5] and MRI images [6]. Specific to PE correction, Vilaça et al simulated the postsurgical cosmetic outcome in patients with PE [7, 8]. The method focused on the skin simulation using a mass-spring model. The cartilages were simply estimated using B-spline interpolation mainly for visualization without quantitative evaluation. Wei et al presented a finite element model of PE based on a single patient CT image. The bones and cartilages were segmented manually using commercial software.

To our knowledge, there are no methods in prior literature to estimate the cartilage in noncontrast chest CT scans due to their poor visibility. In this paper, we propose a method to estimate the anterior surface of cartilaginous structures in the chest by contracting the skin surface to the bone surface. We also simulate the cartilages connecting the centerline of the ribs and the sternum. Our method shows for the first time the cartilaginous surface to better understand the deformation of the costal cartilage of PE patients, providing essential information for whole rib cage modeling and surgical planning.

To estimate the cartilages, the ribs and sternum are first segmented by using interactive region growing and removing the vertebral column with morphological operations. The entire chest wall is also segmented to estimate the skin surface. After the segmentation, surface meshes are generated from the volumetric data and the skeletons of the ribs are extracted using surface contraction method. Then the cartilage surface is approximated via contracting the skin surface to the bones’ surface (ribs and sternum). The ribs’ skeletons are projected to the cartilage surface and the cartilage centerlines are estimated using cubic interpolation given the joints with the sternum. The final cartilage regions are formed by the cartilage surface inside the convex hull of the estimated cartilages.

2. METHODS

2.1 Data

The method was evaluated on five thoracic CT scans of slice thickness 0.62 mm of three healthy subjects and two PE patients (more data is being collected and validated during the time). Each volumetric image consisted of axial images of size 512 ×512 pixels with in-plane resolution ranging from 0.59 to 0.82 mm. The manually segmented cartilages from CT scans by our radiologists were provided as the ground truth.

2.2 Segmentation of Ribs and Sternum

The ribs, sternum and vertebral column are segmented using interactive region growing and smoothed by morphological operations [9]. The seeds are selected manually. To remove the vertebral column from the segmentation, a spatial...
The probability map of the vertebral column is computed by summing up the intensity of each slide along z-axis (from bottom to top), shown in Figure 2. Then the vertebral column mask is obtained by thresholding the spatial probability map. As the vertebral column is not always straight from top to bottom (like a cylinder), the mask is dilated to cover the entire vertebral column area. Then the vertebral column is removed from the volume by applying the mask to each slide. The whole chest wall is also segmented and smoothed using the aforementioned method to estimate the skin surface. This type of segmentation is not applicable to the cartilage, which is poorly, if at all, visible in noncontrast CT. After segmentation, the surface meshes are extracted from both the bones (ribs and sternum) and chest wall (skin) segmentations [10] and smoothed using HC (Humphrey’s Classes) Laplacian smoothing [11]. The HC Laplacian smoothing prevents the effect of shrinking, while preserving the effect of smoothing. The key idea is to push the vertices obtained in each step of iteration of the Laplacian algorithm back into the direction of the original vertices.

![Figure 2](image)

Figure 2. The segmentation of the ribs and sternum: (a) the spatial probability map of the vertebral column and (b) the segmentation of ribs and sternum after removing the vertebral column.

### 2.3 Skeleton Extraction

The skeletons of the ribs are extracted using a mesh contraction method [12]. Given a mesh \( G = (V, E) \) with vertices \( V \) and edges \( E \). The geometric contraction removes details and noise from the mesh surface by applying a Laplacian smoothing. It moves the vertices \( V \) to \( V' \) along their normal directions by solving the discrete Laplacian equation: \( LV' = 0 \), where \( L \) is the curvature-flow Laplace operator

\[
L_{ij} = \begin{cases} 
\omega_{ij} &= \cot \alpha_{ij} + \cot \beta_{ij} \quad \text{if } (i, j) \in E \\
-\sum_{(i,k) \in E} \omega_{ik} & \quad \text{if } i = j \\
0 & \quad \text{otherwise}
\end{cases}
\]

where \( \alpha_{ij} \) and \( \beta_{ij} \) are the opposite angles corresponding to the edge \((i, j)\). The rows in the Laplacian system are referred as the contraction constraints.

To avoid degenerate solutions and ensure that the contracted mesh abstracts the original shape well, all the vertices are attracted to their current positions using soft constraints with different weights, which are referred as attraction constrains. The skeleton is obtained by solving the following equations for the vertex positions

\[
\begin{align*}
V' &= V + L_{ij} \omega_{ij} \quad \text{for } (i, j) \in E \\
V' &= V + L_{ij} \omega_{ij} \quad \text{for } i = j \\
V' &= V + L_{ij} \omega_{ij} 
\end{align*}
\]
\[
\begin{bmatrix}
W_L & 0 \\
W_H & V
\end{bmatrix}
\begin{bmatrix}
V' \\
V
\end{bmatrix}
= \begin{bmatrix}
0 \\
W_H V
\end{bmatrix},
\]

(2)

where \( W_L \) and \( W_H \) are the diagonal weighting matrices that balance the contraction and attraction constraints, respectively. It is equivalent to minimizing the quadratic energy in the least-square sense

\[
\sum_{i} W_L \|v_i' - v_i\|^2 + \sum_{i} W_H \|v_i' - v_i\|^2,
\]

(3)

where the first term corresponds to the contraction constraints and the second term corresponds to the attraction constrains.

2.4 Cartilage Region Estimation

To estimate the anterior surface of the cartilage, we contract the skin surface to the bone surface. As the skin and bone structures are different types of objects, typical registration methods fail to register them directly. In this study, we proposed to register the skin surface and bone structures using surface contraction. The vertices of the skin surface are first projected to the bone mesh and the distances between the vertices and projections are computed as a “distortion map” of the skin surface. The distance values of vertices without projections are interpolated and extrapolated using natural neighbor and nearest neighbor methods, respectively. The natural neighbor method is more accurate than the nearest neighbor, but it does not apply to the extrapolation. Then the vertices of the skin surface are contracted along their normal directions with the amount indicated by the distortion map. The contracted skin surface, touching the anterior surface of the bone mesh, simulates the cartilage surface

\[
v_i' = v_i' - d_i n_i,
\]

(4)

where \( v_i' \) is the \( i^{th} \) vertex on the skin surface, \( d_i \) the distortion value of the \( i^{th} \) vertex, \( n_i \) its normal direction and \( v_i' \) the projected vertex on the cartilage surface. Figure 3 shows the cartilage surface for a normal and a PE case.

The cartilage anterior region is estimated on the cartilage surface. To retrieve the superior and inferior bounds of the cartilage, the skeletons of ribs are first projected on to the cartilage surface mesh. Given the joints with the sternum, the anterior cartilage centerline, connecting the ribs and sternum, is estimated using piecewise cubic Hermite interpolation that preserves monotonicity and the shape of the data [13]. Finally, the cartilage region is formed by the cartilage surface inside the convex hull of the region between the most superior and most inferior estimated cartilages.

The estimated cartilage region is evaluated using the average distance between the anterior vertices of the manually segmented cartilage and the estimated cartilage region.

Figure 3. The cartilage surface: (a) a normal case; (b) a PE case and (c) a CT scan of axial view of the PE case. The deformed region in the PE case has been highlighted with a red circle compared with the healthy case.
3. EXPERIMENTS

The method was evaluated by the distance between the estimated cartilage region and the ground truth. Table 1 summarizes the average errors of the estimated cartilage region of healthy and PE subjects. The results indicate that the contracted skin surface was an appropriate estimation of the cartilage anterior surface, which preserved the deformation of the cartilage of PE patients. Figure 4 shows the distortion map of the skin surface on a healthy and a PE subject. The distortion in the shoulder region was large probably due to the inaccurate extrapolation outside of the area of interest. The estimated cartilage regions are shown in Figure 5 with the color indicating the depth of the surface along the y-axis (from posterior to anterior). It can be seen that the left cartilage region of the PE patient was depressed inward compared to the normal case. Figure 6 shows the error distribution on the manually segmented cartilages. For the normal case, the error of the first six pair of cartilages was small, while that of the region where the eighth cartilage merged with the seventh was larger. It may be caused by the large amount of missing information around that area. For the PE case, the error was mainly distributed in small regions at the bottom of the sternum.

Table 1 Estimation error as distance between the estimated cartilaginous region and the manually segmented cartilage in CT scans of healthy and PE cases.

<table>
<thead>
<tr>
<th></th>
<th>Mean distance (mm)</th>
<th>Median distance (mm)</th>
<th>Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>PE patients</td>
<td>2.15</td>
<td>1.76</td>
<td>2.94</td>
</tr>
<tr>
<td>Healthy subjects</td>
<td>3.63</td>
<td>3.40</td>
<td>5.21</td>
</tr>
</tbody>
</table>

Figure 4 Distortion map of the skin surface computed by the distance between the skin surface and the osseous structures: (a) a PE patient and (b) a healthy subject. All values are in millimeters.

Figure 5 Estimated cartilaginous region with the color indicating the depth along the y-axis (from posterior to anterior): (a) a PE patient showing asymmetry and a chest depression on the left anatomical area, and (b) a healthy subject with
symmetric shape of the cartilages. All values are in millimeters. The smaller the color values, the more depressed the cartilage region to the vertebral column.

Figure 6 Error distribution on the manually segmented cartilage: (a) a PE patient and (b) a healthy subject. All values are in millimeters.

4. CONCLUSION

A method for cartilaginous surface estimation from noncontrast CT scans has been proposed. The ribs, sternum and the whole chest wall were first segmented using region growing method, followed by surface mesh extraction. Then the cartilage anterior surface was estimated by contracting the skin surface according to the distance between the osseous structures and the skin surface. Then the skeletons of the ribs were extracted and projected onto the contracted skin surface. Finally, the cartilage centerlines were estimated by piecewise interpolation and the cartilaginous region was bounded by the convex hull spanned by the approximate cartilage centerlines. The preliminary results showed that the contracted skin surface was a good estimation for the cartilage surface. The simulated cartilaginous region depicted the cartilage deformation of pectus excavatum patients, indicating the severity of the disease. In future work, we will investigate the automatic detection of the joints on the sternum and the estimation of the individual cartilage using machine learning technique. Data collection is ongoing and we will validate the method with more data.

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REFERENCES


