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Development of a High Resolution 3D Infant Stomach Model for Surgical Planning

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1 Introduction

Gastroesophageal reflux disease (GERD) is caused by gastric acid flowing from the stomach into the esophagus. Under healthy conditions, a physiologic barrier called the lower esophageal sphincter (LES) prevents pathologic reflux of stomach contents into the esophagus. GERD is an extremely common disease, affecting between 60 and 70 million people in the United States [2]. Chronic and extreme cases of GERD in infants can cause failure to thrive and damage the esophagus. When medical management fails, a surgical procedure called a fundoplication is performed. The most common fundoplication is the Nissen fundoplication, in which the fundus of the stomach is wrapped around the lower esophagus 360 degrees. This procedure is often performed using laparoscopic (minimally-invasive) surgical techniques. The procedure is not perfect and there is a recurrence rate of 10-15%, especially in infants. The surgeons at Emory Children's Hospital would like to improve the long-term results [2] of fundoplication using low risk system for testing first. We have formed an interdisciplinary team to design such system to meet the medical needs.

We first build two 3D stomach models from in vivo CT scan of an infant, and Visible Human Project (VHP) data provided by the National Library of Medicine [1] (see Figures 1 and 2). Because CT has low spatial resolution, the infant stomach model is coarse. Thus, we improve CT model using the surface normal based morphing [5] and interpolation techniques with high resolution VHP model. Next, we use spring-mass system [4] to model stomach muscle deformation, and use virtual reality haptic device to control deformation upon touching force. To study infant stomach 3D deformation properties, we use videos of infant funduplications.

We use two datasets for our work. The first dataset contains 300+ axial thorax anatomical images from VHP [1] male, with a spatial resolution of 2048×1216 pixels in the cryo-section. We use standard image processing techniques to semiautomatically segment these images into binary representation of stomach walls as shown in Figure 1. The second dataset contains approximately 20 CT axial scans of an infant stomach. The normal configuration of CT generates images in DICOM format with a spatial resolution of 512×512 pixels. We also segment these images as shown in Figure 2.

Next, we use VTK [3] to develop 3D geometric models of stomach. That is, we use segmented images to create VTK volume and render the volume with smooth surface shading. Figure 3 shows the workflow of the whole process. Figure 4 shows the difference in model accuracy. The VHP model is created from 300+ images and is highly detailed, while the infant stomach model is created from ~20 CT scan images and suffers from the loss of details. Thus, the infant model cannot be directly used as a workbench to test new GERD surgical procedures, and has to be improved for more accuracy. In infant stomach CT scans, large variations exist among all successive slices. With many details missing, we decide to use high resolution VHP model to improve the infant stomach model accuracy.

To transform the high resolution 3D VHP male model to best approximate the 3D infant stomach model, rigid registration is needed to align both, and non-rigid registration is needed to cater for local variations. Rigid registration requires a set of points that correspond to each other in both models. So we develop an interface in VTK based on shooting ray method. Shooting ray draws a line from the mouse pointer to the model surface while keeping the camera direction in consideration. The points on the surface will then be used to compute rigid affine transformation. Because the two models originate from two different human subjects (a male adult and an infant), significant morphological differences exist and result in large variation in post-rigid transformation slices.

As shown in Figure 5(a) and 5(b), without deforming the model, when we align one part of the model based on the contour centroid in Figure 5(b), the other parts in the model may be totally misaligned as in Figure 5(a). In addition, certain regions (e.g., stomach outer wall) represented by a single contour in one model, may appear to be two in another model as shown in Figure 5(c). Thus, the two models cannot be registered using only rigid and nonrigid registration techniques.

To address these problems, we have decided to use surface normal based morphing [5] plus information obtained from VHP data, to interpolate images between successive slices of the infant's stomach model. Because an object in one slice may correspond to two objects in the adjacent slice, based on the number of objects in consecutive slices, we classify the morphing into four cases as the following:

Case I: This is the simplest case where consecutive two slices have only one contour with shape variation as shown in Figure 6(a). We first trace the boundary of both contours and compute the normal at each point on the contour as in Figure 7 in an between the two contours. In the next step, between each pair of corresponding points, we compute a series of

points based on constant velocity linear interpolation to generate multiple interpolating images between the slices. This leads to a smooth transition from one slice to the other.

Case II: Considering the two consecutive CT images in Figure 6 (b), the first slice has only one contour and the second slice has two. From the accurate VHP model, we know that one contour slice contains esophagus only, while the other slice also contains main stomach body that just appears in addition to the esophagus. Therefore, we morph the first contour in the first slice to the first contour of the second slice to construct esophagus. For the second contour that does not exist in the first slice, we introduce the centroid of the second contour as the starting point in the first slice. Morphing from this centroid in the first slice to the boundary of the second contour in the second slice generates smooth transition similar to the VHP model.

Case III: The third case in developing the infant's stomach model is when both consecutive slices have two contours shown in Figure 6 (c). In this case, both contours of the first slice are morphed to the corresponding contours on the second slice.

Case IV: In the last case shown in Figure 6 (d), the first slice has two contours while the second contains only one contour. The knowledge from the VHP stomach model suggests that the two contours in first slice are going to merge into one contour. Therefore, before morphing, we merge the two contours into one by creating a line between the closest points on both contours as shown in Figure 7. Then we treat them as single contour to compute interpolating images as explained in Case I.

After computing all the interpolating images, we use VTK to visualize the high resolution version of the infant stomach model. Figure 8 shows the new model developed by morphed interpolation and its comparison with the initial infant stomach model.

Having developed a reasonably accurate model of the infant stomach, our next step is to create a 3D interactive model that reflects stomach deformation upon touching force. More specifically, we want to deform the model surface using 3D interactive devices like haptic device. We first step is to construct 3D stomach model by extracting isosurface. In order to achieve real-time interaction while maintaining smooth movement, we reduce the number of vertices in the model to 1,000. We establish and maintain the connectivity information in a vertex table, where each triplet in this table represents a triangle in the model. Using this information, we then construct a simplified mass-spring system for entire model as shown in Figure 9.

Every vertex is connected to its neighboring vertices with spring that has a restlength measured by Euclidian distance between vertices. The force exerted on one vertex is a sum of forces from all its neighboring vertices. The total force F is determined by:

$$F = \sum_{i=0}^n f_i f_i = k_s (L_c - L_r) + k_d v_s$$

where k_s is the spring constant, L_c , L_r is the current and rest length of the spring respectively, k_d is the damping constant and v_s is the velocity of the spring. In our model L_r and L_c are assigned as Euclidian distance between two vertices at the initial frame and the current frame of the simulation respectively. Figure 9 shows the deformable modeling using spring-damper mass system.

During the simulation, to prevent vertices from spreading out, we add “return spring” proposed by [4]. Return springs have “zero” rest length. They make every vertex return to their home position if there is any discrepancy between the home position and the current position. Figure 10 shows the stomach deformation under two different type of touching forces by haptic devices: pushing and pulling. We execute the simulation on Intel Pentium Core 2 Duo 1.5Ghz CPU, with 2GB of RAM, Windows XP as the OS and Microsoft Visual C++ 8.0 as the development language. The haptic device we use is a Phantom Omni. We have achieved overall 60 fps with a stomach model consisting of 1,000 vertices.

3 Conclusion

In this paper, we have successfully developed a high quality infant stomach model from a low resolution CT scan data by incorporating anatomy information from high resolution VHP stomach data. We have also successfully simulated the stomach deformation upon touch force using a haptic device. By introducing more realistic surface properties to our models, we expect the future models to contain more detailed properties for use in surgical planning.

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Fig. 1.

Few images representing original axial image and segmented stomach walls from VHP. The Figure shows sequence of axial slices from top to bottom (actual data set contains more than 300 slices in stomach region).

Fig. 2. Segmented stomach from infant CT scan data. The Figure shows sequence of axial slices from top to bottom (actual data set contains 21 slices in stomach region).

Fig. 3. VTK workflow for creation and interactivity with stomach model

Fig. 4.
(a) VHP stomach model; (b) Infant stomach model based on CT scans. VHP data-based model is highly detailed and smooth, and the CT-based model is coarse and distorted due to the lack of data and resolution.

Fig. 5. (a) and (b) Sections of two models after rigid registration (c) Dissimilarity in two models resulting in single versus dual contour representation in certain regions

Fig. 6. Different cases for morphing based on number of objects in consecutive slices. Each case is treated separately as explained in relevant section a) Case I, b) Case II c) Case III d) Case IV.

Fig. 7.
For Case IV where two contours are mapped to one. The contours are merged first (L), treated as single contour and morphed to single contour (R) Surface normals are shown in blue.

Fig. 8.
(a) Original infant's stomach model, (b) Improved infant's stomach model by introducing intermediate slices based on morphing and interpolation

Fig. 9.

(a) Mass-Spring model. Every vertex is connected to its neighboring vertices with springs that have rest-length measured by Euclidian distance between vertices. (b) Illustration of the return spring. The vertices moved to “Current Position” at application of force and will return back to “Home Position” when force is removed and return springs length become zero (rest length).

Fig. 10.

(a) Stomach model with 1,000 vertices (b) Pushing force is applied and model deformation seen in the region marked red. (c) Pulling force is applied and model deformation seen in the region marked green.