Haptic Simulation of the Liver with Respiratory Motion.

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Abstract. During a standard procedure of liver biopsy, the motion due to respiration may be difficult to handle. The patient is often requested to hold his breath or to breathe shallowly. Ideally, this physiological behaviour should be taken into account in a virtual reality biopsy simulator. This paper presents a framework that accurately simulates respiratory motion, allowing for the fine tuning of relevant parameters in order to produce a patient-specific breathing pattern that can then be incorporated into a simulation with real-rime haptic interaction. This work has been done as part of the CRaIVE collaboration[1], which aims to build interventional radiology simulators.

Keywords. Haptic rendering, Physiological simulation, physically-based modelling

Introduction

Interventional radiology is a technique that uses imaging to guide needles or catheters through organs using minimal access into the body. Basic skills are still taught in an apprenticeship in patients. Our aim is to build a virtual simulator to train in image-guided needle puncture procedures. Imaging data sets for simulation of image-guided procedures would alter dynamically in response to deformation forces such as respiration and needle insertion.

While several research groups have used organs in the abdominal cavity (e.g. liver) in their modelling efforts, their work has been done all but in isolation from the surrounding organs / structures, concentrating instead on the interaction between the surgical tool and the topic area of the operation. Interactions such as touching, grabbing, inserting and cutting have been studied in the past. However, the abdominal cavity can be subjected to natural and procedure specific dynamics: all the organs in the abdominal cavity are below the diaphragm and the rib cage and hence follow the respiratory motion. A recent survey on needle insertion into soft tissue [Abolhassani07] states that one of the key challenges is to accurately model the real environment, including respiratory motion.

Here we propose a framework for combining respiratory motion and haptic interaction. Our focus is first on a preliminary medical study, followed by a description of the

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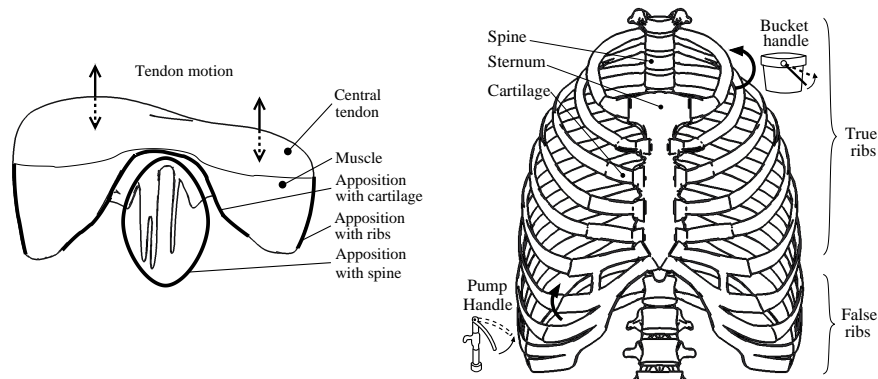
Figure 1. Respiration physiology. *Left:* diaphragm behaviour with apposition zones, *right:* Ribs motion

input data as well as the simulation method. The last sections present the results of our simulation framework and summarise our conclusions.

1. Anatomy and physiology concerns

Respiration is a physiological process that can be separated into two main contributions: the thorax motion with the intercostal muscles allowing the ribs to rotate, and the diaphragm action whereby the diaphragm muscles contract or relax during the breathing cycle.

1.1. Diaphragm

The diaphragm (Figure 1.*left*) can be considered as a sheet of tendon and muscle. The diaphragm muscle attaches to the chest wall and its fibers radiate inwards inserting into a Central Tendon. The zone of apposition is that part of the diaphragm that is apposed an inner aspect of the rib cage. The circumferential part is muscular. During inspiration, the lowest ribs are fixed; and from these and the crura the muscular fibers contract and draw the central tendon downwards and forwards with the attached pericardium. In this movement, the curvature of the diaphragm is scarcely altered, the dome moving downwards nearly parallel to its original position and pushing before it the abdominal viscera. The descent of the abdominal viscera is permitted by the extensibility of the abdominal wall, but the limit of this is soon reached. The central tendon, applied to the abdominal viscera, then becomes a fixed point for the action of the Diaphragm, the effect of which is to elevate the lower ribs and through them to push forwards the body of the sternum and the upper ribs. The right cupola of the diaphragm, lying on the liver, has a greater resistance to overcome than the left, which lies over the stomach, but to compensate for this, the right crus and the fibers of the right side generally are stronger than those on the left.

1.2. Rib cage

The thoracic skeleton is mainly composed of ribs (Figure 1.*Right*). Ribs are elastic arches of bone, and a typical human ribcage generally includes 24 ribs, 12 on each side. The first seven ribs, also called true ribs, are connected to the spinal column and, via costal cartilages, to the sternum. The five remaining ribs - or false ribs - are composed by three ribs whose cartilages are attached to those of the rib above. The last two are known as floating ribs since they are not attached at the front. The space between two ribs is called intercostal space and contains intercostal muscles causing their motion during respiration. The movement of the ribs can be considered as the combination of a "bucket handle" movement and a "pump handle" movement. The "bucket handle" movement increases the lateral excursion of the ribs, while the "pump handle" one increases the anteroposterior diameter of the thorax. Thus, the rib cage diameter increases in both the anteroposterior and the transverse directions.

2. Materials and methods

Our two main objectives are the ability to customize the simulator for each patient, as well as to simulate the breathing at a high enough rate to enable haptic interaction. Bearing this in mind, this section deals with how the data have been acquired and preprocessed, as well as with the methods used to model the motion and deformation of the target organs.

2.1. Data aquisition and pre-processing

The ultimate product is a liver biopsy simulator customized to a patient for training any surgeon on the real case before executing it. The organ geometries for the modelling are extracted from medical imaging data sets. More specifically, we have used anonymised CT scans from the Royal Liverpool Hospital. The organs were segmented using ITK-SNAP [5], while the bones were obtained using the levelset method. Each rib (12 left and 12 right) and the spine have been uniquely labelled to have independent motion. The diaphragm has been manually segmented and validated by an expert.

Once the patient's anatomy has been extracted from the CT scan, the data needs to be pre-processed. Firstly, a triangular surface mesh is generated in order to 1) smooth the boundaries, thereby removing the CT scan pixel discontinuity, and 2) have less elements during the simulation, which will save computational time and memory storage. Volumetric tetrahedral meshes are then generated using the CGAL library[2] with a mesh angle of 5, mesh distance of 1, and mesh radius of 1. The mesh is smoothed using `vtkWindowedSincPolyDataFilter()` with a pass band of 0.2, followed by a 50% decimation, followed by another 200 iterations of Windowed Sinc smoothing.

Secondly, geometrical parameters have to be extracted from the mesh to facilitate the simulation. Concerning the ribs, we will assume them as rigid bodies and only compute their rotational motion. In our case where only static CT scans are available, the rotation of the ribs is obtained by computing the moments of inertia for each rib followed by their eigenvectors. From these, a plane for each rib can be determined and used to obtain the

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[2]http://www.cgal.org/

rotation points by finding the intersection between each rib plane and the the spine axis. Concerning the diaphragm, the pre-processing step consists in determining the central tendon part in order to correctly apply the boundary conditions. The tendon part is then approximated by a plane used to constrain the motion.

2.2. Physiological modelling

As previously said, the respiration may be be separated into the thorax motion and the diaphragm action. The modelling of both behaviours in our simulator is described in this section.

2.2.1. Ribcage modelling

As explained in §1.2, the rotation of the ribs can be defined by the combination of two different rotations: the "bucket handle" and the "pump handle" movement. They are respectively defined here by the angles α and β. Wilson *et al* [7] measured these angles for five subjects at Functional Residual Capacity (FRC) and Total Lung Capacity (TLC). The rib rotation was thus decomposed into two distinct rotations. We consider here that the rest position is at FRC. In our model, the rotation angles are given by the following equations:

$$\alpha' = ((\alpha_{\text{TLC}} - \alpha_{\text{FRC}}) \times \tfrac{1}{2} \times (1 + sin(2\pi f t)) \tag{1}$$

$$\beta' = ((\beta_{\text{TLC}} - \beta_{\text{FRC}}) \times \tfrac{1}{2} \times (1 + sin(2\pi f t)) \tag{2}$$

where:

- α' : reduced "pump handle" angle $\alpha'(\text{FRC}) = 0$ and $\alpha'(\text{TLC}) = \alpha_{\text{TLC}} - \alpha_{\text{FRC}}$
- β' : reduced "bucket handle" angle $\beta'(\text{FRC}) = 0$ and $\beta'(\text{TLC}) = \beta_{\text{TLC}} - \beta_{\text{FRC}}$
- f : respiration frequency
- t : time

2.2.2. Diaphragm modelling

Although the ribs were modelled as a rigid body, such assumption is not possible for the diaphragm. The method used for the deformation modelling is based on the 3D Chain-Mail algorithm extension proposed by Li and Brodlie [8]. In this model, the object is defined as a set of point elements. The elements are interconnected as links in a chain. So, within a certain limit, each point can move freely without influencing its neighbours. When one element of the object is moved and reaches this limit, the neighbours are forced to move in a chain reaction that is governed by the stiffness of the links in the mesh. The ChainMail parameters to simulate the deformation behaviour include the compression, the stretching and the shearing.

The movement of the diaphragm has two main features. The first is due to the contraction of the muscle and the rotation of the ribs. The diaphragm is contracted and looks smaller. Secondly, the central tendon moves almost parallel with the transverse plane.

To model the central tendon as a tendon and not as a muscle, it has to be almost rigid. This can be done by setting the ChainMail parameters to specific values. When the compression parameter is equal to 1, the stretch parameter is equal to 1 and the shear
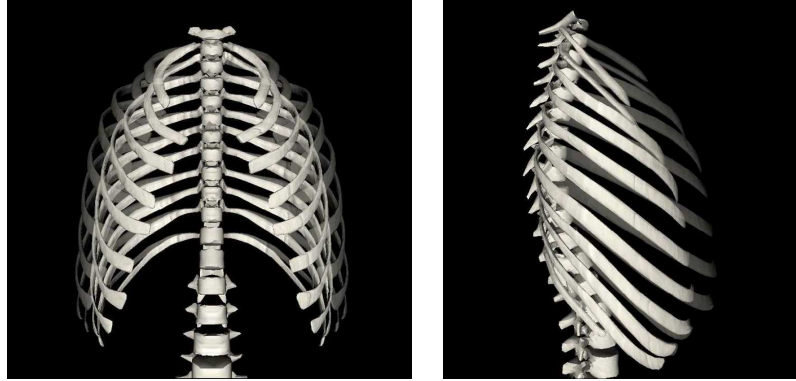
Figure 2. Rotation of the ribs at FRC (bright) and TLC (dark). *Left :* anterio posterior view, *right :* lateral view

parameter is equal to 0, the object is rigid. To do a vertical movement, one central point is forced to have a sinusoidal movement along the vertical axis similary to Equation 1 and 2. During inhalation, the central tendon has a downward movement, which is synchronous with the expanding rib cage. As the links for the central tendon are rigid, the points corresponding to this tendon will follow the exact same movement. The other points will have the expected "chain reaction" according to the ChainMail rules.

At FRC, the diaphragm has a shape like what can be seen in Figure 1.*left*.Thus, it must be able to compress itself during inhalation. The chosen value for the compression parameter is 0.7. The stretch and shear components are not very important here. The value for the stretch parameter and the shear parameter are 1.1 and 0.1, respectively. However, the diaphragm is also supposed to follow the movement of the ribs. To do, this the idea is to "fix" some points of the diaphragm to some points of the ribs.

Finally, the movement of the diaphragm will be a combination of the downward movement of the central tendon and the movement induced by the contact points with the ribs.

3. Results

Our Framework has been developed inside the H3D API[2]. H3D is an open source, scene-graph API. It is entirely written in C++, and it uses OpenGL and HAPI for graphics and haptic rendering. Our implementation runs in real-time with haptic feedback and can be fine-tuned by adjusting the simulation parameters, e.g. if the patient is holding his breath or suddenly having a normal tidal breathing. 4 patient datasets have already been converted into this haptic simulator.

Figure 2 shows the rib cage motion of our simulator. The volume of the rib cage increases in both anteposterior and the transverse direction during inhalation. The rotation of the ribs is decomposed in a "bucket handle" movement (Figure 2.*left*) along the dorso ventral axis and a "pump handle" movement (Figure 2.*right*) around the left-right axis.

To obtain a realistic movement of the diaphragm, two contact points for each side have been defined. The diaphragm is thus in contact with the 10th and the 11th ribs. There are thus 4 constrained points due to the movement of the ribs. Furthermore, the
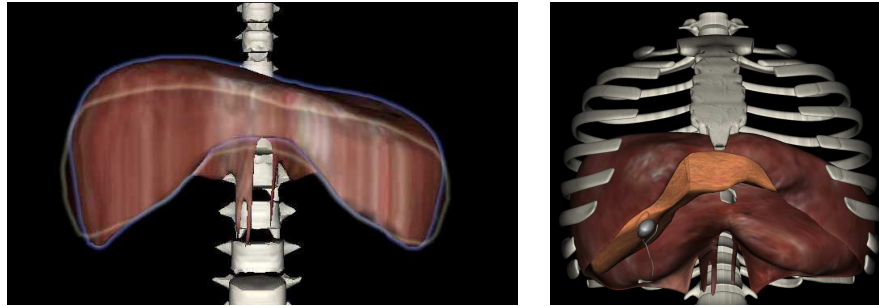
Figure 3. *Left :* Shape of the diaphragm at FRC (contour line) and TLC (inside line), *right :* all the organs

central tendon is also moving with one central point. Figure 3.*left* shows the diaphragm motion during the simulation. As expected, the diaphragm looks smaller at TLC. The liver has been attached to the diaphragm with 4 points and therefore follows its motion (Figure 3.*right*).

Conclusion

We have presented a dynamic 3D virtual environment that supports interaction via a haptic device. The physiological boundary conditions have been rigorously studied to improve the realism of liver biopsy by adding the respiration process. Our model has been positively evaluated by clinical collaborators, but further quantitative validation is required.

As part of our future work, we will model the needle insertion inside the organs and couple it with our motion model. Validation studies for the complete simulation will also be undertaken.

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