Percutaneous Transhepatic Cholangiography Training Simulator with Real-time Breathing Motion

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Purpose

Interventional radiology procedures are minimal access interventions where medical imaging is used to guide instruments within various organs to perform a range of therapeutic procedures. One of these, percutaneous transhepatic cholangiography (PTC), makes use of a needle to access dilated bile ducts within the liver for diagnostic and therapeutic purposes. Real-time X-ray imaging (fluoroscopy) is used during the injection of a radiopaque contrast medium to identify any stone or tumour obstructing the biliary tree. The skills required to perform such a procedure are typically acquired during an apprenticeship in patients. Inexpert manipulations by the trainee, however, can produce pain and complications, as well as increasing the procedure time. Using optimised algorithms for simulating respiration and fluoroscopy, we propose a computer-based simulation as an alternative to train the procedural skills needed in PTC.

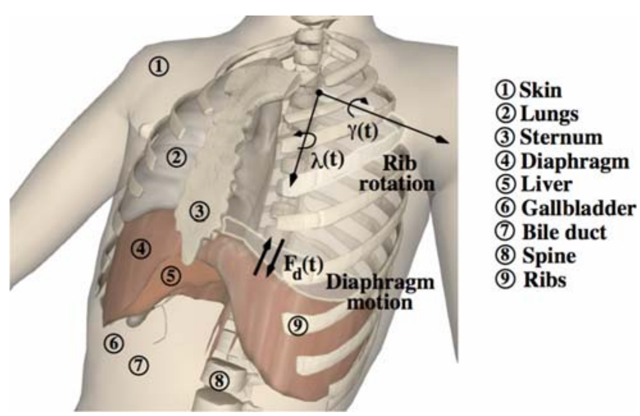

Fig. 1 Respiration modelling: rib kinematics and diaphragm forces parameterisation

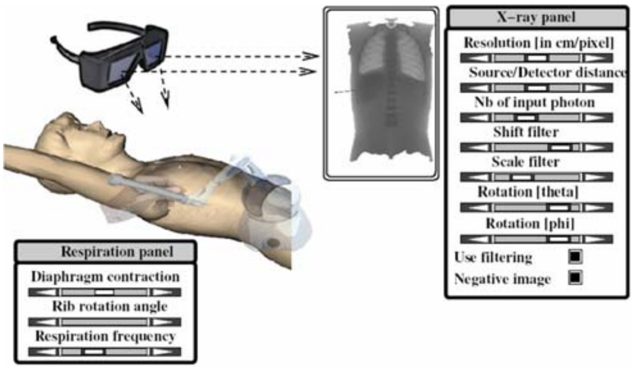

Fig. 2 PTC simulator with haptic device and 3D glasses

Methods

A task analysis for PTC has been carried out to identify the key elements that must be included in the virtual environment and also the level of fidelity required for each component of the simulator.

The first aspect to model is respiration because of its consequences for the behaviour of visceral motion during the procedure. The breathing process can be simplified to be cyclical and can be modelled using a sine wave. We developed two independent mathematical models for the diaphragm and the ribcage. The diaphragm is modelled as a heterogeneous organ composed of muscles and a tendon. This latter has an upward and downward motion that follows the breathing curve whose amplitude is tunable. The muscle component is made up of 3D ChainMail elements [1] that passively follow the tendon. The ribs are assumed to be rigid and follow a kinematic motion where their rotation angle is linked to the breathing curve. All of these kinematic values are tunable within the simulation. Figure 1 summarizes the organs and boundary conditions of our respiration model.

The second aspect to model is fluoroscopy, which is used to guide needle placement and to monitor the contrast injection. The fluoroscopic simulation is based on the Beer-Lambert law (also called attenuation law). We adapt the X-ray simulation algorithm developed in [2] to take advantage of the PC Graphics Processing Unit (GPU). It makes use of temporary images to store the path length of rays for each organ. Using path length images, the total attenuation is then computed using the attenuation law. An image smoothing filter is applied locally to correct the artifacts that may arise in the path length images. Figure 2 shows a fluoroscopy image produced from a breathing patient in real-time.

Finally, the haptic rendering is integrated to the virtual environment. First, the bones are rigid bodies and a stiff contact is provided when the needle touches the spine or the ribs. Then we provide a force to constrain the needle to follow a straight line once the length of the shaft within the body reaches a given threshold. Finally, the soft tissue response is computed for each organ punctured by the needle. The force feedback has been implemented as in [3]. It behaves as a succession of exponential-like rises before and after liver capsule penetration.

Results

Our algorithms have been implemented in C++ and make use of the H3D API (www.h3dapi.org). All the computations are performed using the CPU, except the fluoroscopy simulation task, which is implemented in parallel on the GPU. This makes it possible to achieve interactive performance. The graphic rendering is performed at 70 Hz whilst 1024 Hz are maintained for the haptic rendering. Five training scenarios have been created using patient specific data. Figure 2 shows an example of one of these environments and how the user can interact with the simulator. Stereoscopic 3D shutter glasses allow the user to see the patient skin in 3D and help him/her with the positioning of the needle. Similarly to the interventional suite, the 2D fluoroscopic image is displayed on a dedicated monitor. With one hand the user is handling the needle via the haptic device. A force feedback is rendered to the user during the insertion of the needle. Finally, a control panel is available to control the respiration behaviour and the fluoroscopic rendering.

Conclusions

We have presented a novel simulator to perform PTC. The contents have been dictated by a detailed task analysis. It includes real-time respiratory motion with two independent parameters (rib kinematics and diaphragm action), on-line fluoroscopy implemented on the GPU and haptic feedback to feel the soft-tissue behaviour of the organs during needle insertion.

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