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Development of a Surgical Simulator for Laparoscopic Esophageal Procedures

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***Abstract*—This paper describes a surgical simulator of laparoscopic esophageal procedures with virtual reality (VR) technology for training purposes. Because the success of the procedure is highly influenced by the number of practices, a VR based simulator is a promising training medium in terms of safety and expense. For the realistic simulation of tool-tissue interactions, a physically based soft tissue model of the esophagus and an algorithm of cutting on the lower esophagus skin are implemented. The tissue parameters from *in vivo* animal experiments are combined with geometric organ models segmented from the Visible Human Dataset and integrated into the laparoscopic surgical simulation system consisting of haptic interface devices inside an abdominal mannequin and a graphic display. This system can be used to demonstrate deformation and cutting of the esophagus, where the user can haptically interact with the virtual soft tissues and see the corresponding organ deformation on the visual display simultaneously.**

I. INTRODUCTION

GASTROESOPHAGEAL reflux disease (GERD) is quite common: approximately 7% of Americans experience GERD daily [1]. GERD is caused by a malfunction in the lower esophageal sphincter (LES) where the muscle connects the esophagus to the stomach. In a serious case of GERD deterioration, surgery can become mandatory. Nowadays, laparoscopic fundoplication is preferred to conventional open surgery because the procedure can significantly reduce the incision size, thus expediting post-surgical recovery. The most common procedure for GERD is Nissen fundoplication, which involves both the anterior and posterior sides of the esophagus. Another method is Heller's myotomy, a partial laparoscopic fundoplication, that only involves the anterior side. Both surgery procedures consist of two major processes: a shallow tissue incision and suture of the esophagogastric junction or diaphragm.

Significant failure rates have been reported for laparoscopic fundoplication, and reoperation due to various complications is not uncommon - approximately 8% of operations need reoperation. Fortunately, these procedures have a definable "learning curve" obtainable from clinical data. Figure 1 is the clinical data from Australian hospitals where more than 280 procedures were performed by a total of 11 surgeons from 1991 to 1995 [2]. This graph shows that the complication rate, reoperation rate, and medical operation time for this operation were significantly reduced over the number of operations. In other words, the success of the procedure is highly influenced by the number of practices.

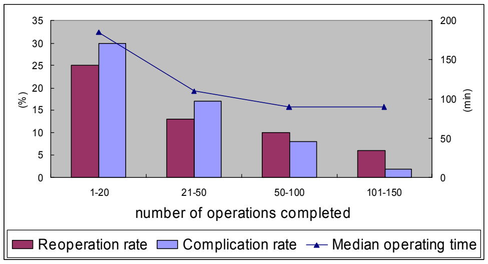

Fig. 1. Failure rate and operating time with respect to the number of the operations by surgeons in Australian hospitals [2].

Due to the safeness and capacity to provide repetitive training opportunities, VR-based surgical simulation can be considered as a promising training tool. This technology can provide a structured learning experience, permitting practice without danger to patients and facilitating the teaching of rare or unusual cases. In order to provide the trainee with a realistic environment, the simulator must provide a realistic simulation of interactions between the surgical instruments and biological tissues.

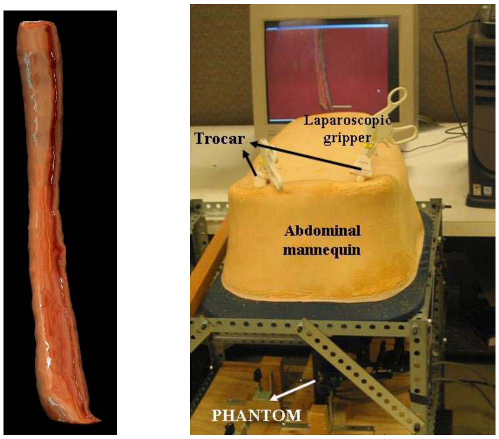

Fig. 2. (a) Esophagus model and (b) simulator setup for laparoscopic esophageal procedures.

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Although several VR surgical simulators have been developed, there are relatively few simulators for esophageal procedures compared with other procedures such as cholecystectomy [3], colonoscopy [4], or bronchoscopy [5]. De *et al*. performed a simulation of the palpation of an esophagus model for the treatment of an esophageal motility disorder using a meshless technique [6]. Yassi *et al*. presented an anatomically-based mathematical model of the esophagus for off-line analysis [7]. However, these researchers focused largely on the development a model of the esophagus rather than on the entire system of the simulator.

II. IN THIS PAPER, THE DEVELOPMENT OF A SURGICAL SIMULATOR FOR ESOPHAGEAL PROCEDURES IS PRESENTED. THE TISSUE PARAMETERS WERE COMBINED WITH GEOMETRIC ORGAN MODELS SEGMENTED FROM THE VISIBLE HUMAN DATASET AND INTEGRATED INTO A MINIMALLY INVASIVE SURGERY (MIS) SIMULATION SYSTEM CONSISTING OF HAPTIC INTERFACE DEVICES INSIDE A MANNEQUIN AND A GRAPHIC DISPLAY. FOR THE SIMULATION OF TISSUE INCISIONS ON THE LOWER ESOPHAGUS AREAS, A SURFACE-BASED INCISION SIMULATION ALGORITHM IS ALSO PRESENTED. SYSTEM DESCRIPTION

Figure 2 (b) shows the simulator setup at the Touch Lab/ M.I.T. The setup includes a rubber abdominal wall, with surgical instruments and trocars inserted at similar positions to those in real operations. Underneath the abdominal wall, the surgical tools are connected to PHANTOM (SensAble Technologies) haptic interface devices. Laparoscopic surgeons have noted that forces by the abdominal wall at the trocar are the dominant forces during surgery, and are much greater than the smaller forces between the tools and the organs [8]. It would be technically challenging to simulate both the abdominal wall forces and contact forces simultaneously. Therefore, a rubber abdominal model is used so that only the forces between the tools and the intra-abdominal structures need to be modeled.

III. METHODS

A. Geometrical Modeling

A three dimensional geometrical model of the esophagus from the Visible Production (http://visiblep.com) is used, as shown in Figure 2 (a). This model is segmented from the Visible Human Dataset, released by the National Library of Medicine (NLM) [9]. Because the original model has too many detailed surfaces, the model is simplified in 3D StudioMax by Discreet (www.discreet.com). The simplified model has 1836 vertices and 3726 triangles. For a more realistic appearance, the texture image obtained from the laparoscopic video is attached to the geometrical model using the environmental texture mapping technique [10]. This technique can display the deformation of the esophagus model with a glistening effect in real time together with less computing resources.

B. Material Modeling

For accurate simulation of tool-tissue interactions, an accurate material model of the esophagus is required. In particular, data from the living state is more desirable because the material properties of soft tissues change drastically after being removed from the body. To obtain *in vivo* data, the mechanical behavior of a pig's esophagus was measured under open surgical conditions at the Harvard Center for MIS in collaboration with surgeons from the Massachusetts General Hospital (MGH). A total of 10 pigs were used in these experiments [11]. Because the material parameters such as viscoelasticity could not be inferred explicitly from the experiments, a characterization algorithm based on continuum mechanics was developed to extract the material parameters from the experiments. In short, a three dimensional FE model combined with an optimization program is employed to calculate the forces at the indenter and find the material parameters simulating the behavior of the esophagus during the experiments (A detailed description of the characterization algorithm can be found [12]).

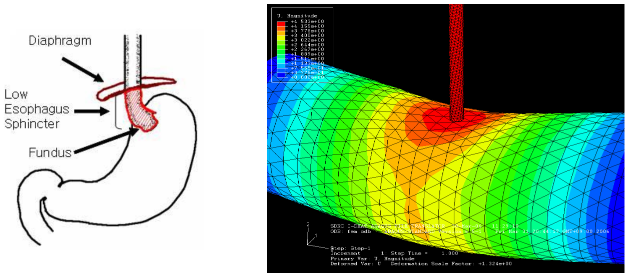

Fig. 3. (a) Esophagus and its anatomical location and (b) FE modeling for the material characterization.

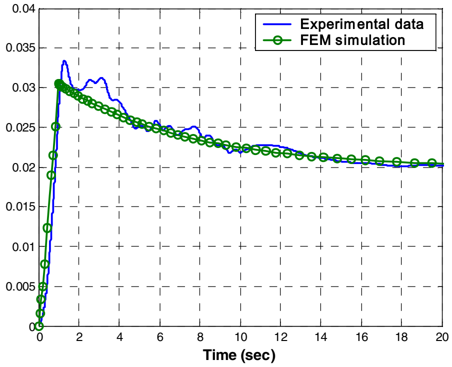

Fig. 4. Comparison of experimental data and FEM model prediction.

Because consideration of the entire esophagus requires too much computational resource and, moreover, appears to be unnecessary, the model was simplified as follows. The target procedures treat only a small region called the abdominal esophagus and the lower esophageal sphincter (LES), both of which are located at the end of the esophagus. Therefore, we only take into account these parts in the modeling. The abdominal esophagus is modeled as a tubular structure 60 mm in length. Because the abdominal esophagus is tightly connected with the diaphragm at the upper end and the fundus (the upper part of stomach) at the lower end, both ends can be modeled as fixed ends for simplification. 30 mmHg internal pressure is also modeled in the simulation [13]. Figure 4 shows the simulated response of the esophagus. The Young's modulus of the esophagus is estimated from inverse FEM modeling to be 5.222 kPa. The relaxation time constant and the 1st order of Prony parameter for viscoelastic modeling are 6.372 and 0.363 sec, respectively. These numbers are used as parameters of the physically based organ model to compute the interaction forces during the simulation in real time.

C. Simulation of Tool-Tissue Interaction Force

A physically based soft tissue model is employed to compute the organ deformation including the interaction forces at the surgical instrument. To this end, an approach developed by James and Pai has been implemented, wherein the boundary element method (BEM) is applied for computing the organ deformation in real time. The BEM is based on the discretization of the integral equations of motion posed on the surface of the model. It has significant advantages over volumetric techniques for the modeling and analysis of linear elastostatic problems [14]. In the BEM, the boundary of the domain under consideration is tessellated using "elements." Using piece-wise constant interpolation (i.e., the displacements and tractions are assumed to be constant over each element), a BEM equation of linear elastostatics with 'n' elements is given by

$$c\mathbf{u}_i + \sum_{j=1}^{n} \Big(\int_{\Delta_i} p^* \Phi^T d\Gamma \Big) \mathbf{u}_j = \sum_{j=1}^{n} \Big(\int_{\Delta_i} u^* \Phi^T d\Gamma \Big) \mathbf{p}_j \qquad (1)$$

where Δ_i is the surface of the i^{th} element, and u^* and p^* are the 'fundamental solutions' [14]. $\mathbf{u}$, $\mathbf{p}$, $\mathbf{\Phi}$ are displacement and traction vectors at a point **x** in the domain or on the boundary and interpolation functions, respectively. The coefficient 'c'in (2) depends on the smoothness of the boundaries and can be found in the literature (for a smooth boundary, $c = 0.5$) [14].

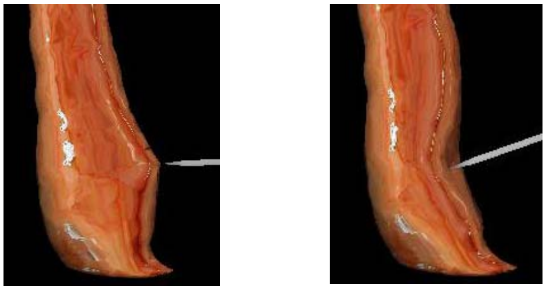

Fig. 5. palpation simulation of the lower esophagus model.

Satisfying this equation at the center of each element and incorporating the boundary conditions, the following system of linear algebraic equations is obtained:

$$\mathbf{AY} = \mathbf{F} \qquad (2)$$

where $\mathbf{Y}$ is a vector of length N (N=3n) and contains the unknown deformations and tractions at the centroids of the boundary elements. **A** is N x N dense matrix. **F** is the known right hand side vector containing the boundary conditions. Since the use of precomputation and structural reanalysis techniques results in a very rapid computation procedure [15], this model can provide both visual deformation around the tool-tissue interaction area and haptic feedback through the haptic device.

D. Cutting Algorithm

In Heller's myotomy, the circular muscle at the level of the esophagogastric junction is incised. For this procedure, tissue incision of the lower esophagus must be included in the simulation as well as deformation.

However, it is extremely difficult to simulate cutting of soft biological tissues by using accurate modeling of the physics in real time due to heavy computational requirement. This necessitates not only real time remeshing of the model but also induces numerical complexities: elimination of the old model, recreation of the new model, and computation of the stiffness matrix. A few relevant works related with cutting simulation have been reported. Bielser et al. [16] used a lookup table to reduce the complexity involved in the creation of new elements for each cut element. Mor and Kanade [17] generated a minimal set of new elements to replace modified tetrahedral elements during progressive cutting. Although these are very important steps to reach the goal of accurate cutting simulation, it is still challenging for these schemes to provide enough realism for the simulation with realistic appearances. To achieve minimum interactivity of the cutting of the esophagus skin, a surface-based cutting technique based on a pure graphical technique was developed [18]. It modifies only graphic models following a cutting path and displays visual feedback in real time as the progress of the cut shape is generated.

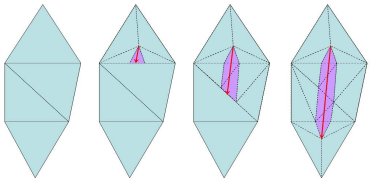

Fig. 6. Surface subdivision with a tool path

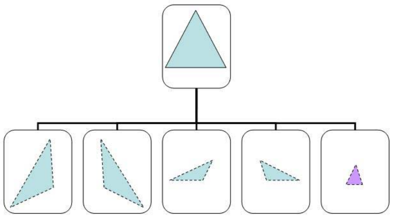

Fig. 7. The hierarchical database between the original polygons and the dividing polygons

In this cutting procedure, after the initial contact between the cutting tool and the first intersecting polygon on the organ surface, the simulation algorithm records where the tool passes. Whenever the tool moves into an edge of the neighboring polygons, the cutting algorithm divides the polygon where it previously passed into several polygons (Figure 6). A hierarchical database is then constructed with respect to the relationship between an original polygon and the divided polygons (Figure 7). In addition, each divided polygon is discriminated in terms of whether the tool has passed over it. Using this data base, the algorithm allows the divided polygons to be drawn instead of the original cut polygons.

For improving visual realism, the cut polygons are constructed with a low resolution model. This makes cut surfaces easily distinguishable from the surrounding surfaces. Figure 8 shows a cutting simulation on the lower esophagus area.

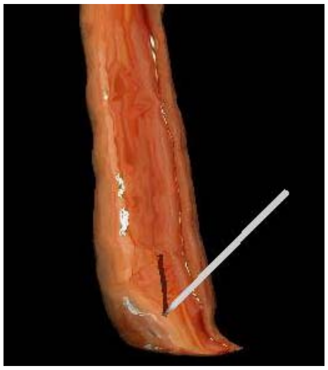

Fig. 8 Cutting simulation on the lower esophagus model.

IV. CONCLUDING REMARK

This paper has reported on a VR based simulator for esophageal procedures that provides realistic haptic and visual responses to a user in real time for training purposes. The soft tissue properties from *in vivo* animal experiments are characterized using several biomechanics models and estimation algorithms. A three dimensional esophagus model based on the Visible Human Dataset for simulation is developed. The model supports limited opening of skin tissue and mid-level (up to 20 mm) deformation caused during gripping and palpation. In real MIS scenarios, as more surgical procedures are performed, more complex algorithms, such as those for scraping and excising pathological tissues, are required in the simulation.

A possible extension of the simulator is the modeling of nonlinear and nonhomogeneous behavior of the esophagus. The esophagus consists of multiple layers with different material properties, and thus modeling of these is necessary for some surgical procedures [7]. Much interesting work remains to be developed for more realistic simulation of tool-tissue interactions such as detection of self-collision, organ-organ collision, and effective torque rendering, as well as force rendering, with respect to the current haptic rendering algorithms. Since a certain level of precomputation is unavoidable for real time rendering, effective strategies for precomputation of the global model can also be further improved.

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