GPU-Friendly Gallbladder Modeling for Laparoscopic Cholecystectomy Simulation

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Abstract— A challenge in virtual reality based laparoscopic cholecystectomy simulation is to construct a fast and accurate deformable gallbladder model. This paper proposes a multi-layer mass-spring model which can well adapt to the built-in accelerating algorithms in PhysX-engine of GPU. The gallbladder is first segmented from clinical CT images. A multi-layer model based on the anatomical structure of gallbladder is subsequently constructed. We configure the parameters of the springs based on the biomechanical properties of gallbladder to ensure the realism of the deformation results. Preliminary experiments demonstrate that our model can achieve satisfactory results in terms of both visual perception and time performance.

Keywords- laparoscopy; surgical simulation; mass-spring;

I. INTRODUCTION

Surgical training has always been one of the most important components in the surgeon’s career development. Traditionally, surgical training is done with the ‘master-apprentice’ strategy where the trainee has to learn the surgical procedure by repeating the steps as performed by the master after having observed his/her master perform it several times. With increasing complexity of the surgical operations nowadays, it becomes increasingly dangerous for the trainee to “learn” while operating on a real patient despite being supervised during the operation. To meet the patient need for more specialty surgeons, a good advanced surgical training system is important to provide surgical skill training and assist pretreatment planning.

Laparoscopic cholecystectomy is one of the most popular interventions. According to Federal Citizen Information Center, there are 500,000 Americans each year having gallbladder surgery and 80% are performed using laparoscopes [1]. Although laparoscopic cholecystectomy is popular and quite safe, there are some cases complication can occur. A Consensus Development Conference panel convened by the National Institutes of Health, noted that “it should be performed only by experienced surgeons”. Currently, there are simulation training instruments [2, 3, 4] that allow the trainees to “dry-run” on standard operations with fixed operative scenarios. These instruments therefore lack the variety of difficult operative situations encountered in real-life surgeries. In addition, certain maneuvers by an experienced surgeon that is required for such situations cannot be easily taught to the trainee. A patient specific laparoscopic cholecystectomy simulation system could help the junior surgeons to learn the surgical procedure in a fast and safe way.

However, it is difficult to develop a robust laparoscopic cholecystectomy simulation system. One of the challenges is to construct a fast and accurate deformable gallbladder model to interactively and realistically simulate the behaviors of gallbladder during the interventions. In this paper, we propose a novel and fast mass-spring modeling of gallbladder for laparoscopic cholecystectomy simulation. The multi-layer model constructed based on the anatomical structures approximates the behaviors of gallbladder and facilitates the assignment of viscoelastic parameters to it. A bimodular elasticity modeling scheme is adopted to approximate the nonlinear viscoelastic properties of gallbladder. More important, the proposed model can well adapt to the built-in accelerating algorithms in PhysX-Engine of newly released Graphics Processing Unit (GPU). Thus we can take use of the parallel mechanism of GPU to greatly accelerate the complex physical model computations. Preliminary experiments demonstrate that our model can achieve satisfactory results in terms of both visual perception and time performance. The rest of the paper is organized as follows. We review related works in Section 2, work out our GPU-friendly model in Section 3, report experiment results in Section 4 and draw conclusions in Section 5.

II. RELATED WORK

Recently, some works have been devoted to developing laparoscopic cholecystectomy simulation systems. Lee et al propose a laparoscopic cholecystectomy simulator with force-feedback device [5]. Although this simulator can improve the realism through real-time interaction between force-feedback and visual-feedback, the deformable model is too simple to realistically simulate the biomechanical properties of
gallbladder and surrounding tissues. Webster et al propose a mass-spring-damper gallbladder model for laparoscopic cholecystectomy simulation [6]. In this model, they incorporate an approximate solver that pre-computes the solution to a linear system to accelerate the computations. However, the matrix generation process of the solver may take several minutes or even longer depending on the number of polygons in the organ model. Hence, the speed of the system cannot be guaranteed, especially when the geometry models are complex. Tendick et al propose a virtual environment testbed for training laparoscopic surgical skills, where critical steps of the cholecystectomy are provided [7]. However, it cannot provide realistic deformable results as it focuses on parallel processing of physical modeling and rendering for real-time interactions between virtual instruments and deformable organs and pay little attention on the parameters configuration of the models to ensure the realism.

Due to the rapid improvement in the Graphics Hardware in recent years, researchers attempt to exploit the processing power of GPU and special physics processing units (PPU) for mass-spring models and finite element models [8, 9, 10, 11]. As GPU is capable of processing multiple streams of data with the same program in parallel, it is beneficial to the modeling of mass-spring model which requires updating all springs and masses iteratively in the same manner. Thus, the performance gain from GPU is expected. Compared to previous works, we aim at exploiting the PhysX-engine equipped in newly released GPU to accelerate the physical computations for our proposed model.

III. METHOD

A. Multi-Layer Mass-Spring Modeling

When virtual surgical simulation is applied for surgical training and surgical planning, realistic contact forces and graphical deformation is indispensable. Therefore accurate modeling biomechanical behavior of human organ in virtual surgical simulator is essential. Although numerous techniques have been proposed for simulation of human organs’ biomechanical behavior, few can provide the performance to meet surgeon’s requirements. Accuracy and interactivity are always the main tradeoff in the surgical simulation. In our implementation, a multi-layer mass-spring modeling approach is proposed based on the segmented CT images of gallbladder.

In the multi-layer model construction, the segmentation of the gallbladder from original CT images can be done manually or semi-automatically. With the extracted gallbladder surface, several subsequent iterations of erosion of this surface will result in the creation of a set of distance iso-surface. The segmented surface is defined as the outer surface and all other generated surface are inside this outer surface. The distance between the generated first layer of surface and the outer surface is about 2mm which is the estimated wall thickness of the gallbladder, as reported by Engel in [12]. The distance from the first layer to the other two inner layers are 1/6 and 2/5 of the whole gallbladder width. In the implementation, the first two-layer structure is used to model the biomechanical behavior of the gallbladder wall and the rest structure to model the inner bile behavior. Thereafter, the extracted surface is used to generate surface meshes which are stored as a list of triangular facet in an obj format file. The multi-layer mass-spring model is automatically obtained based on the surface meshes using the following steps:

- Every triangle in the upper surface projects its centroid in the normal direction to hit the lower surface layer.
- The intersection points are used as the mass vertices in the lower layer.
- Springs are added to connect those vertices in the original triangle and its projected centroid. A tetrahedral mesh structure between the next two surface layers is thus constructed.
- A triangulation process is carried on these projected centroids.
- Similar procedures are iterated for the lower layers until all the layers are processed.

Fig. 1 shows a complete construction process for a virtual gallbladder extracted from a CT dataset. In Fig 1(c), for example, the green color springs represent the connections between masses of the same layer and the purple color springs represent the connections between masses of different layers.

B. Bimodular Viscoelastic Modeling

Many of the existing surgical simulators model the human tissues as simple linear viscoelastic materials. Nevertheless, various biomechanics literatures [13, 14] reported that the elastic properties of body tissues are not simply linear. For example, the stress-strain relationship of human gallbladder tissue illuminates an exponentially increasing form, where the
stiffness increases slowly at the beginning and relatively faster after the tissue is stretched to a certain extent. Inspired from it, a bimodular stress-strain relation is proposed to approximate the elasticity of the gallbladder tissue.

To model the bimodular elastic behavior in real-time, a bimodular mass-spring system (BMS) is implemented to accurately simulate dynamic effect of gallbladder tissues in a timely manner. Generally, a mass-spring model is built from hundreds of masses connected by springs. Therefore, the macroscopic viscoelasticity of the whole BMS is contributed by every individual spring in the system.

As stated in [11], we can obtain the desired macroscopic bimodular viscoelasticity in the whole BMS with proper tuning of the bimodular elastic parameters of individual springs. Finding microscopic viscoelastic parameters is thus reformulated as an optimization problem to search the proper setting of viscoelastic parameters for every individual spring. Simulated annealing algorithm [15] is suitable for seeking a global optimal solution without the need to evaluate the first derivative in the objective function. To simplify the problem, each layer within the multilayer model is optimized independently. Besides, springs in each layer are divided into two groups based on their major effective direction: normal and tangential directions. Such a division is similar to the tissue structural arrangement. Each group is then assumed to have the same viscoelastic spring parameters.

Mathematically deriving the macroscopic viscoelasticity of the mass-spring model from the microscopic behavior of each spring is not very efficient in modeling procedure. Instead, an empirical approach is used to acquire the macroscopic behavior. Similar to normal biomechanical experiments in obtaining mechanical properties of human tissues, a virtual experiment is carried out by applying various stresses on our multilayer model as shown in Fig. 2. In this sense, corresponding macroscopic viscoelastic properties $\kappa$ can be obtained. As mentioned above, different elastic properties need to be tuned in normal and tangential directions to approximate their anisotropic properties. Therefore, each group of springs are optimized separately based on the objective function given by Equation 1,

$$\kappa = \sum_{i} \mu_i (\frac{p_i}{q_i} - 1)^2$$  \hspace{1cm} (1)

where $p_i$ is the evaluated value of i-th parameter from the experiment, $q_i$ is the corresponding desired value for the particular tissue from biomechanical literatures, $\mu_i$ is the weighting for the parameter.

In the virtual experiments, to compute the macroscopic elasticity of the mass-spring model, we determine the stresses required to induce certain levels of strain. The recorded data are then processed by linear regressions in order to obtain bimodular properties like stiffnesses and turning strain. The samples are divided into two groups based on the applied strain. The grouping with minimum regression error is chosen since it best fits the bimodular relation. The two stiffness $K_1$ and $K_2$ are computed accordingly. The interception of the two lines is used as the changing point.

![Figure 2. Experiment on collecting macrostructural stress-strain relation of multi-layer model. (a) model at rest state and to apply force on it. (b) masses are stretched with a length $L$.](image)

Viscosity $\eta$ is similarly determined using the following equation:

$$f_v = \eta \nu = f_e - Ks - ma$$ \hspace{1cm} (2)

where $f_v$ is the viscosity stress, $f_e$ is the external force; $m$ is the mass; $a$ is the acceleration, $\nu$ is the velocity, $K$ is the stiffness, and $s$ is the strain. By applying various stresses $f_e$ on the BMS, the variables in the right side of Equation 2 such as $\nu$, $s$ and $a$ are tracked. Thereafter, discrete samples of the relation between $f_v$ and $\nu$ are used to estimate the viscosity $\eta$ by simple linear regression.

The optimization process evaluates the objective function repeatedly until a minimum is obtained. All viscoelastic parameters are optimized in the same manner, while the macroscopic viscoelasticity acquisition experiments are performed under different directions.

C. Mass-Spring Modeling on GPU

GPU provides built-in linear mass-spring system acceleration. Similar to a typical BMS, we can define the mass of an individual node and the viscoelasticity of an individual spring. As illustrated in Fig. 3(a), Washabau in [16] reported the non-linear property of the stress-strain relationship of gallbladder. The elastic stress-strain curve has the following key parameters: compress force, compress length, initial length, stretch force and stretch length. To model the bimodular elastic behavior of gallbladder, we extend the GPU-built-in linear mass-spring to support a bimodular spring which composes two linear springs. Firstly, from the curve, we derive the two groups of linear stress-strain relations represented by optimal stiffness $K_1$ and $K_2$. Subsequently, our solution is to place these two linear springs with different elastic configurations in parallel. The idea is to make the two linear springs being activated separately in the two different phases of the stress-strain curve. Fig. 3(b) shows how the two linear stress-strain curves are combined to form the bimodular curve.

Comparing to a linear spring, the bimodular spring has two more parameters which are the changing point and changing force, referring to where the change of stiffness takes place. The decomposition of bimodular spring into two linear springs can be easily derived and automatically computed during
creation of the deformable model. We should notice that the compression forces of spring 1 and 2 can be set to any arbitrary values between zero and the compress force of the bimodular spring, while the only requirement is that their sum must be equal to compress force the bimodular spring (BS). In our simulations, we set them as half of compress force of BS. When setting the parameters of spring 1, the compress length value is the BS compress length; the stretch length value is the BS changing point; the stretch force is set as the value of (changing force – compress force of spring 2) and the initial length is set as the value of (compress force/\(K_1\) - compress length). Similarly, in spring 2, the compress length value is the changing point; the stretch length is the BS stretch length; the stretch force is set as (BS stretch force – stretch force of spring 1) and the initial length is set as (compress force/\(K_2\) - compress length).

![Stress-Strain Curve](image)

**Figure 3.** The stress-strain curve (a) linear spring defined in GPU, (b) a bimodular spring composed of two linear springs.

D. Visualization

The mesh resolution of gallbladder surface used in the mass-spring model representation is not dense enough from the visualization point of view, extra enhancement on the surface mesh would be necessary for generating higher rendering quality. In our implementation, the mesh model (also called physical model) was used to calculate the deformation arose from the interaction of gallbladder and surgical tools in a physics engine component. The graphics engine then maps the texture of gallbladder to the mesh model. Fig. 4 shows the whole rendering process, which is accelerated by shading programming technique using GPU.

![Geometric and Physical Models](image)

**Figure 4.** Geometrical model and physical model interaction.

IV. Results

A GeForce 9300 graphics card in a Pentium 4 3.20 GHz was used for the presented simulation and visualization. A detailed (2190 masses) model of a human gallbladder was reconstructed from a CT dataset.

Significant speed improvement is observed when CPU and GPU are employed in pushing and pulling simulation. In the process of visualization, the average frame rate of the GPU-based system is 20.16 Frame/Second for a volume of 128*128*128 in size while the corresponding frame rate for the CPU-only system is only 0.86 Frame/Second. The visualization results of the virtual gallbladder deformation based on our modeling framework are shown in Fig. 5. Fig. 5 (a), (b) and (c) show the deformations under one pulling force and pushing force.

![Visualization Results](image)

**Figure 5.** Visualization results of the gallbladder deformations based on our mass-spring model, (a) deformation caused by a pulling force, (b) deformation caused by a pushing force, (c) deformation caused by a pushing force in a different angle.

V. Conclusions and Future Work

The patient specific mass-spring modeling of gallbladder is a key element in the laparoscopic cholecystectomy training and planning system. A simple but efficient bimodular viscoelastic modeling method was proposed to simulate the biomedical behavior of gallbladder. Extended from the GPU-built-in linear mass-spring structure, two linear springs were used to compose a bimodular mass-spring system. The modeling results were used in the integrative system which is a new attempt to integrate a robotic assistive practice and assessment technology to mimic a master-apprentice learning process. PhysX-Engine of GPU was used to accelerate the mass-spring deformation. Experiments reveal that our model supports a real-time surgical simulation to train and test various laparoscopic skills such as locating the gallbladder in the abdomen, grasping and turning the gallbladder properly, locating and dissecting the cystic duct, clipping the cystic duct and cutting the cystic duct.

Nevertheless, the modeling method still needs further improvement for more realistic simulation. For example, since the gallbladder consists of a layer of smooth muscle, it is subject to both active and passive tensions. The active tension is generated by hormonal stimuli, and the passive tension is caused by stretch of the muscle. The constitutive equation between the active force and length variation in the gallbladder need to be studied in strips of gallbladder using uni-axial experiments [16].
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