

INTEGRATING BIOMECHANICAL PARAMETERS IN MODELING OF LIVER WITH AND WITHOUT TUMOR IN VIRTUAL ENVIRONMENT

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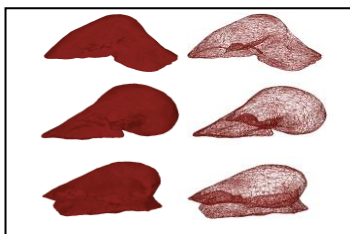
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Graphical abstract



Abstract

One of the fundamental components of a surgical simulator is a deformable object. Two main approaches used in surgical simulation to model deformable objects are Finite Element Model (FEM) and Mass Spring Model (MSM). MSM is often preferred due to its simplicity and low computational cost. However, setting of appropriate model parameters such as mass, spring stiffness and damping coefficients in order to reproduce mechanical responses remains an issue. In this paper, biomechanical parameters (Poisson's values, density) are integrated into MSM based on a tetrahedral structured network in modeling of liver with and without tumor. For the identification of parameters in a real time surgical simulation, Barycentric mass lumping, Lloyd's approach, Rayleigh formula and Fourth order Runge-Kutta integration method are used to determine the node mass, spring stiffness, damping coefficient and suitable time step respectively. The resulted node mass, spring stiffness and damping coefficient for liver without tumor and with tumor are 1.9825kg, 5.4225 kPa, 7.4525 N/m² and 5.9256kg, 7.0484 kPa, 11.9012 N/m² respectively. These values are substituted into MSM, which is then visualized in CHAI 3D ensuring the performance required by a real time simulation. Finally, comparison between the liver with and without tumor in terms of mass, spring stiffness, and damping constant is highlighted.

Keywords: Mass-spring model, biomechanical parameters, liver tumor, real-time simulation, surgical simulation

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1.0 INTRODUCTION

Surgical simulation is widely used in medical field. It provides technical training and skill practice to surgeon in a simulated environment before actual surgery is performed on real patients [1]. Besides, it can enhance novice surgeons' surgical skill and build their confidence for the real surgery [2].

In the past, surgical training is practiced on animal, cadavers, or real patients. Animal organ is not same with human organ, as the size (dimension and

thickness) of animal organ does not accurately represent human organ. Meanwhile, the properties of cadavers are different from real life organs in terms of mechanical responses, topology changes, nonlinearity, and viscoelasticity behaviors. In addition, having surgical training done on real patients may cause tension to the surgeons as minor mistakes may lead to death. Hence, surgeons will easily lose confidence, as the risk is high [3].

Liver cancer is one of the leading causes of cancer death worldwide [4]. There are many treatment

options available for liver cancer such as liver transplantation, liver resection, ablation techniques, chemotherapy, targeted therapy and radiation therapy [5]. One of them is surgical liver resection, a revolutionary surgical technique to treat liver cancer. It has always been challenging because of excessive blood loss during the operation which may reduce the survival rate of the patient. In order to master the skill of liver resection, surgeons need to train their skills in identifying accurately the tumor location and size in a virtual environment. Hence, surgeons can perform the operation with low risk [6].

Mass Spring Model (MSM) and Finite Element Model (FEM) are two most popular approaches used in surgical simulation of physics-based deformable objects. Both models apply numerical integration techniques in modeling the objects involving physics engine based on difference equation of continuum mechanics theory. FEM is very accurate and realistic but the computational requirement makes FEM hard to be applied in real time and interactive simulation [2]. On the contrary, MSM which is made up of simple structures requires relatively small computational cost [7]. As a result, MSM is well-suited to model soft tissues for real-time surgical simulation [8] where the trade-off between computational accuracy and speed will have to be taken into consideration.

The common issue for MSM is the determination of suitable parameters such as spring stiffness and damping coefficients which usually are determined through trial and error [1]. Researchers have proposed several different methods in determining the appropriate MSM parameters. However, it still remains an issue. The aim of this paper is to model liver tissue with and without tumor for comparison with a real liver tissue. The virtual deformable model used in this paper is based on MSM with a tetrahedral structure; vertex is called node where mass is applied, and edge is referred as link, on which linear spring is applied. This model is not just a 3D surface mesh. It is a physical representation in which geometry and topology of the primitive elements are combined with biomechanical properties. Figure 1 shows the models of virtual human liver.

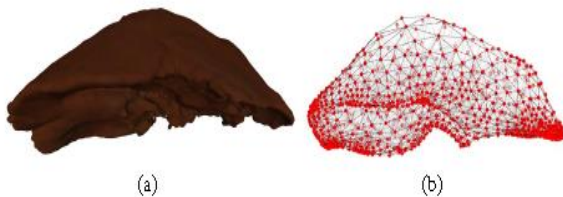


Figure 1 (a) shows the 3D surface extracted from medical dataset while (b) shows an example of mass spring model of liver in real time simulation [2]

2.0 METHODOLOGY

For this research, data generated by computerized tomography (CT) scan were used to get detailed

three-dimensional (3D) images of liver with and without tumor. This dataset is represented in 3D matrix of scalar values that contains vertices and edges. Each vertex and edge represents a point mass and a spring respectively. Subsequently, MSM parameters such as mass, damping and spring constant were calculated and integrated into an equation of motion of a simple one-dimensional MSM system with a single mass as given in (1),

$$m\ddot{x} + b\dot{x} + kx = f_{ext} \quad (1)$$

Where m, b, k, f_{ext} are mass, damping constant, spring constant and external force respectively [9].

2.1 Determination Masses of Nodes

A widely used approach to determine masses of nodes is to consider only the diagonal terms, corresponding to the components of each node. Lumping allows an intuitive physical association where mass is applied to each node. For each node, the three mass components are considered equal, when node mass, m_i to be determined is a simple scalar value.

Mass, m_i can be computed with known density ρ of the surrounded volume. Barycentric mass lumping is the common procedure to establish this association between the volume and density. It contributes mass to each node, defined by the set of the tetrahedron. Hence, the node mass m_i is derived from the sum of the mass contributions calculated for each incident on the node i .

Meanwhile, the barycentric subdivision scheme splits each tetrahedron into four volumes, each referring to one of its nodes. Considering the uniform density, each mass contributes to each node of the tetrahedron. Hence, the formula to compute the mass for each of node is as in (2),

$$m_i = \frac{1}{4} \sum_{t \in \Omega_i} \rho_t V(t) \quad (2)$$

Where Ω_i is the set of tetrahedra sharing the node i , while ρ_t and $V(t)$, are respectively the density and volume of the tetrahedron t . Figure 2(b) shows the set of tetrahedra sharing the node i .



Figure 2 (b) depicts red tetrahedra that share the same red node in (a); (c) shows the tetrahedra in blue incident on the blue spring - edge in (a) [2]

2.2 Determination of Spring Stiffness Coefficient

Generally, the connection between two points is modeled using linear spring, where the force exerted by the spring connecting two generic nodes i and j , is proportional to the elongation of the spring k_{ij} . In order to calculate the spring coefficient, Lloyd's approach is applied. This method compares the stiffness matrix derived from FEM formulation with spring's network derived from MSM, obtaining (3),

$$k_{ij} = \sum_{t \in \Omega_{ij}} \frac{2\sqrt{2}}{25} l_t E \quad (3)$$

where spring coefficient connecting the vertices i and j is computed considering the set Ω_{ij} of tetrahedra sharing the ij edge. Figure 2(c) shows the set of tetrahedra sharing the spring.

2.3 Determination of Damping Coefficient

Damping deals with realism and stability of mechanical systems. One of the most used and straightforward method in determining damping coefficient is the Rayleigh formula, as given in (4),

$$D = \alpha M + \beta K \quad (4)$$

where α and β are proportional to the mass and stiffness respectively. However, due to unavailability of instrument in conducting the test for organ damping parameters, the Rayleigh formula has been used to determine damping coefficient D .

2.4 Determination of Suitable Time Step

During simulation, numerical integration method solves a generalized MSM model, which can be represented by a set of ordinary differential equations as given in (1). In this paper, Fourth-order Runge-Kutta method has been adopted to solve (1) with several choices of time step because of its popularity and ability in achieving high level of accuracy for real-time simulation [10].

The experiment started with simulation time step of $h=1$. The system ran for 10 seconds from $t=1.0$ to $t=10.0$. It was rerun with new time steps ranging from 1.0 to 0.005. System stability was calculated from the value of the solution. If the solution converges and trends to zero, then the system is considered stable [9].

3.0 IMPLEMENTATION

The implementation phase requires the usage of several softwares. It starts by inputting CT datasets into NETGEN, open-source mesh generation software [11], to generate volumetric representation of tetrahedral meshes for liver with or without tumor. Once the network is defined, tuning of nodes, springs and damping has to be applied. Barycentric mass lumping must be implemented to compute mass

contributions for each tetrahedron. Similarly, springs properties have been evaluated to determine volumes required to solve (3). Finally, Rayleigh damping coefficients α and β are applied to each node. After the parameterization phase, the resulting structures are graphically rendered using CHAI 3D relying on its functionalities such as collision detection and force response. Figure 3 and 4 displays the visualization result of liver without and with tumor model in CHAI 3D respectively.

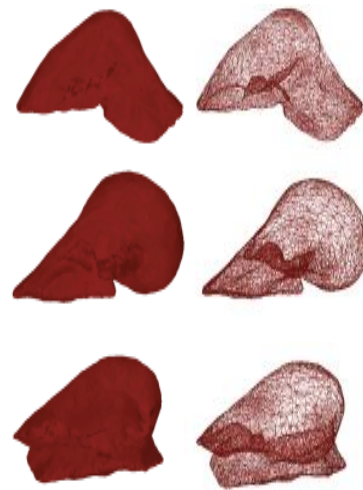


Figure 3 Liver without tumor in CHAI 3D

Figure 3 displays the front view and side view of the solid and wire-framed liver model without tumor. This model consists of 15806 sets of tetrahedrons. Meanwhile, the liver model with tumor as shown in Figure 4 has 19478 sets of tetrahedrons. When inspecting models in Figure 4, the tumors with six different sizes of lesions can be easily spotted.

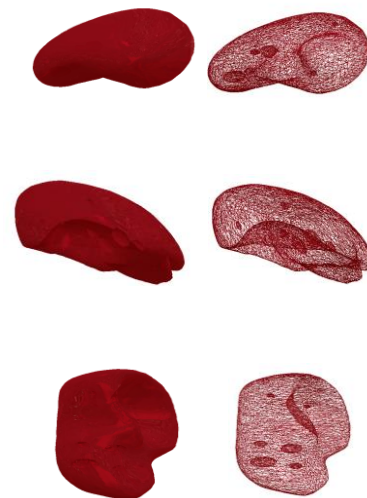


Figure 4 Liver with tumor in CHAI 3D

4.0 RESULTS AND DISCUSSION

4.1 Parameters

Table 1 shows the result of the parameterization of liver with and without tumor. Based on the simulation result given in table 1, the parameters obtained for liver without tumor have satisfied the ideal range of $0.118kg < 1.9825kg < 2.0994kg$ for mass, $2.1kPa < 5.4225kPa < 17.5kPa$ for spring stiffness, and $4.5 N/m^2 < 7.4525N/m^2 < 40N/m^2$ for damping constant. Hence, this proves that the above parameters are suitable to be used in real time simulation of a deformable liver.

On the other hand, the parameters benchmark values for liver with tumor model are not available as this may be due to lack of interest or has not been taken up by researchers yet. Therefore, its results can only be compared with the result of liver without tumor where values of mass, spring, and damper coefficients are found to be higher than the liver without tumor.

Due to the presence of tumor in the liver, the mass of liver with tumor model is found to be higher than the liver without tumor model, which is $1.9825kg < 5.9256kg$. However, the mass of liver with tumor model will continue to increase as the tumor grows bigger which may lead to liver becoming heavier. In addition, the spring stiffness value of liver with tumor model is also found to be significantly higher than the liver without tumor model, $5.4225kPa < 7.0484kPa$. With the larger stiffness value, the liver with tumor model is expected to be much stiffer compared with the liver without tumor model. Consequently, the damping value of liver with tumor is also higher than the liver without tumor model which cause the model to become damper.

Table 1 Parameters for liver with and without tumor models

Model	Mass (kg)	Stiffness (kPa)	Damping (N/m ²)
Without Tumor	1.9825	5.4225	7.4525
With Tumor	5.9256	7.0484	11.9012

4.2 Suitable Time Step

Figure 5 and 6 show the stability of different time step sizes of $h = 0.005, 0.05, 0.5$ and 1 in liver with and without tumor respectively. Red and green region indicate as unstable region while the white region representing a stable region. From Figure 5 and 6, it can be clearly observed that the green line ($t = 0.005$) converges to zero, where it does not fall into unstable region and remain in the stable region after the simulation runs for 10 seconds. Therefore, both models maintain stability at time step size, $t = 0.005$.

It is important to observe the time step size for both models particularly when the time step, $h = 1$ is

applied in liver without tumor model, the solution decreased from 1 to -0.1. Nevertheless, when time step size, $h = 1$ is applied in liver with tumor model, the solution decreased from 1 to -1. This shows that when the same time step sizes is used for different systems, it will generate different results. Furthermore, the time step size, $h = 1$ was not able to maintain stability in both systems. This proves that a large time step size would lead to the collapsing of the system.

On the other hand, when a small enough time step is applied to the system, it will maintain stability. For example, when the time step size, $h = 0.005$ is substituted into liver with and without tumor models, the solutions converge to zero and remain in the stable region even after 10 seconds. As a result, it can be concluded that a small enough time step is needed to maintain stability in MSM.

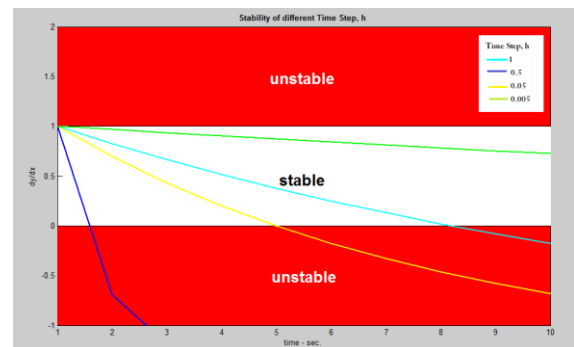


Figure 5 The stability graph of distinct time step sizes, $h = 0.005, 0.05, 0.5$ and 1.0 in liver without tumor

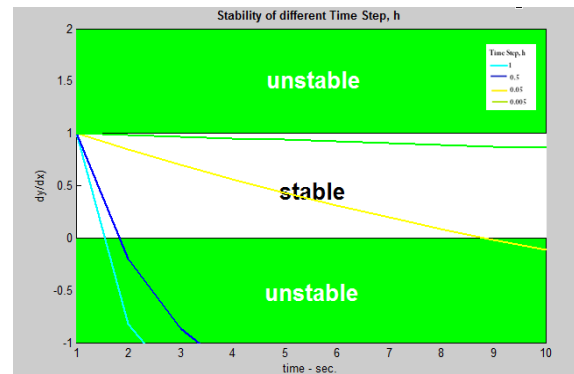


Figure 6 The stability graph of different time step sizes, $h = 0.005, 0.05, 0.5$ and 1.0 in liver with tumor

5.0 CONCLUSION

5.1 Summary

This paper presents a virtual model based on a parameterization of biomechanical properties. It consists of a mass spring model with a tetrahedral structured network, in which nodes are characterized by masses, and damping coefficients, while links are described by spring stiffness constants.

Simulations in this paper were performed on a notebook: Intel Core i5-2430M, 2.4 GHz with 8 GB RAM running a 64 bit Microsoft Windows 7 Home Premium. The tetrahedral meshes were generated using NETGEN 4.9.13. Mathematical calculations were developed using Microsoft Visual Studio 2010 with C++ language and MATLAB R12(a). For graphical environment, CHAI 3D was used to visualize the deformable objects and user interaction.

The results for this paper are the visualization of virtual liver with and without tumor. Figure 5 and 6 shows the virtual liver with and without tumor in CHAI 3D. Both of these models have different parameters values of mass, spring stiffness, and damping constants. Meanwhile, both liver models can easily be differentiated by observing the presence of tumor.

5.2 Future Work

Although this paper successfully visualizes the liver with and without tumor, there is still a significant improvement needed in the development of the simulation. Future work on this project includes improving the realism of the liver by adapting more biomechanical and behavioral parameters. Improvement on haptic devices applied on virtual liver model such as simulating the needle insertion. Last but not least, simulation on removing tumors from the liver.

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