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A high-fidelity virtual liver model incorporating biological characteristics

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ABSTRACT

Flexible tissue modeling plays an important role in the field of telemedicine. It is related to whether the soft tissue deformation process can be accurately, real-time and vividly simulated during surgery. However, most existing models lack the unique biological characteristics. To solve this problem, we proposed a high-fidelity virtual liver model incorporating biological characteristics, such as the viscoelastic, anisotropic and nonlinear biological characteristics. Besides, to the best of our knowledge, our study is the first to introduce the viscoplasticity of biological tissues to improve the fidelity of the liver model. This mothod was proposed to describe the viscoplastic characteristics of the diseased liver resection process, when the liver is in a state of excessive deformation and loss of elasticity, however, there are few works focusing on this problem. The 3DMax2020 and OpenGL4.6 were used to build a liver surgery simulation platform, and the PHANTOM OMNI manual controller was used to sense the feedback force during the operation. The proposed model was verified from three aspects of accuracy, fidelity and real-time performance. The experimental results show that the proposed virtual liver model can enhance visual perception ability, improve deformation accuracy and fidelity.

1. Introduction

Outbreaks of infectious diseases such as COVID-19 have highlighted the importance of using telemedicine technology in a crisis. The telemedicine technology not only provides more convenient treatment for patients, but also helps government deal with sudden risks and protect medical workers. Among them, virtual surgical modeling has always been the key to research, especially the processing of flexible tissue deformation. Designing a high-fidelity flexible body model is more conducive to doctors' surgical operations, thereby achieving accurate contact and cutting. So, it is an urgent need to model complex flexible body tissues with higher fidelity in this field. For example, there are some key issues in the virtual surgical simulation process of liver model cutting, such as the balance between real-time performance and accuracy as well as the fidelity of deformation-cutting process simulation. To achieve these goals,

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one must consider the fact that the flexible body tissues have many unique biological characteristics, such as viscoelasticity, anisotropy and nonlinearity. How to reflect these characteristics in the modeling is also a key to surgical modeling. As the largest gland in the body, the liver is the sole one that can regenerate and perform vital functions to sustain life. However, liver cancer is one of the most common malignancies with a significantly higher mortality rate than other cancers. Fortunately, if the cancer cells in patients with primary liver cancer do not metastasize to other organs, early surgical resection of the cancer cells contributes a chance of survival for patients, and the five-year survival rate after surgical resection can reach 40%–70 %. Therefore, simulating liver cutting and deformation during surgery is particularly important, which will affect the success rate of surgery. It is crucial to design a high-fidelity liver surgery model to promote the development of telemedicine.

In addition to the above-mentioned biological characteristics of the soft tissue, the viscoplastic characteristic of biological tissue can reflect whether the cancer cells have migrated to some extent [1], it can also reflect the viscoplastic deformation process of soft tissue before cutting and breaking, which is beyond the scope of viscoelastic deformation. However, most researchers have neglected the viscoplastic deformation process. In view of this, this study constructs a new model to simulate the nonlinear viscoplastic deformation process by incorporating the viscoplastic characteristic into the finite element model, so as to improve the realism of the deformation simulation of virtual liver surgery. The contributions of this study are twofold:

- To the best of our knowledge, this is the first to simultaneously incorporate multiple biological characteristics including viscoelastic, nonlinear and anisotropic properties into the liver model to obtain a virtual liver model with higher fidelity. Incorporating multiple biological characteristics of the liver can make the deformation process of the virtual liver tissue more vivid and realistic during the operation, thereby enhancing the experience of the doctor.
- In addition, when simulating the resection of a diseased liver, the model undergoes a plastic deformation process where loses elasticity due to excessive deformation but does not reach the critical point of fracture. Compared with other similar methods, instead of only considering viscoelastic characteristic, this study is the first to consider the viscoplastic characteristic during surgical cutting to simulate the whole process of creep deformation of virtual liver tissue before being cut and break, making the simulation process more vivid and complete, which improves the fidelity of the virtual liver model.

This article is structured as follows: The second section discusses the previous work; The third section outlines the proposed methods; The experimental results, including model accuracy, fidelity, and real-time performance, are presented in the fourth section; Finally, the fifth section provides a summary of the article.

2. Related work

In the past decades, physical modeling methods have been widely studied and applied to modeling and simulation of biological tissues. Among various modeling methods to enhance the immersion of virtual surgery, scholars from many countries are committed to balancing the real-time and authenticity of the model, and most of them believe that biological tissues are purely elastic [2–9]. Abbass Ballit et al. [2] proposed a new mass spring model for fast, accurate, and stable simulation of dynamic soft tissue deformation. Bin Dong et al. [3] replaced the spring with a cylindrical traditional mass spring model by a multi-component conical spring and proposed a new multi-component conical spring model. In addition, there are many studies on finite element method, because it has the advantage of accurate modeling. In order to accurately and real-time simulate the simulation process of soft tissue during surgery, Wenguo Hou et al. [4] incorporated the relationship between soft tissue and a new energy function virtual instrument representing interaction constraints into the derived optimization problem. Jinao Zhang et al. [5] proposed a finite element algorithm based on fast explicit dynamics, which could realize rapid thermal analysis of tissue deformation state. Jon S. Heiselman et al. [6] used linear iterative boundary reconstruction of sparse surface and vascular features to correct liver deformation intraoperatively to avoid large errors caused by soft tissue deformation. Hujin Xie et al. [7] proposed a new method for real and real-time modeling of deformable biological tissues by combining the traditional finite element method with the constrained Kalman filter, which was utilized to address the deficiencies of the finite element method with large computation amount and inherit the advantages of physical fidelity at the same time. Sirui He et al. [8] introduced the virtual cutting simulation algorithm based on the energy-based cutting fracture evolution model to conduct real-time and real cutting simulation for the multifunctional cutting fracture evolution modeling of deformable objects. Xiaorui Zhang et al. [9] successfully addressed the computational challenges of the derived equations in lung finite element modeling by employing the high-precision variable step size fourth-order Runge Kutta method and optimizing the step size selection. This approach resulted in good simulation outcomes. Based on this, this paper also used this method when calculating the complex partial differential equations of the liver model, to give consideration to the precision and real-time capabilities of the model.

However, although the above method can simulate the physical characteristics of soft tissue deformation in a real and real-time manner, they often ignore or do not pay attention to some biological characteristics of flexible tissue in order to avoid complex calculation. At this time, scholars will try to introduce a constitutive model to accurately simulate as many biological characteristics as possible. This task is not easy because these biological characteristics represent very complex phenomena such as nonlinearity, direction-dependent anisotropy, and time-dependent viscoelasticity. Some scholars began to notice the influence of these biological characteristics on the deformation of virtual surgical models, and some research results have been achieved [10–14]. Wei Zhang et al. [10] used the generalized Maxwell model to fit the relaxation data of the aorta and capture the significant features of vascular viscoelasticity by taking the rate insensitive characteristics of biological materials into account. Yanni Zou et al. [11] proposed a new soft tissue model based on radial basis functionalized point interpolation, integrating Kelvin viscoelasticity into the proposed model to represent the relaxation, creep and hysteretic characteristics of soft tissue. Hujin Xie et al. [12] combined the traditional nonlinear finite element method and nonlinear Kalman filter to solve the physical fidelity and real-time performance of soft tissue modeling, and proposed an innovative method for real simulation of nonlinear deformation behavior of biological soft tissue. Yang Zheng et al. [13] proposed a porous ultra-viscoelastic model liver for shear-wave elastography, which is helpful to promote the use of shear-wave elastography in disease diagnosis. Wenguo Hou et al. [14] proposed a deformation model based on the optimized implicit Euler method, and incorporated the anisotropy and viscoelastic behavior of brain tissue.

Although many researchers have proposed various schemes for modeling the biological characteristics of flexible tissues, there are still some problems, such as the model is not vivid and the description of biological characteristics is not comprehensive. In addition, none of the above studies considered the influence of viscoplastic properties on the deformation of soft tissue models. Viscoplasticity refers to the plastic properties that lose elasticity due to excessive deformation but have not reached the critical point of fracture. It can be used to simulate the viscoplastic deformation of soft tissues before they are cut. Ovijit Chaudhuri et al. [1] pointed out that biological tissues have the characteristics of viscoplasticity, and viscoplasticity has an impact on the migration of cancer cells. Therefore, it is very urgent to express and study the model viscoplasticity. However, there are few references for soft tissue viscoplastic deformation simulation. From an engineering point of view, the mechanical behavior of some objects can be modeled according to the constitutive laws [15–21]. Since both constitutive models of soft tissue and salt rock can be simulated with Kelvin based models, inspired by the methods adopted by other scholars in studying the creep characteristics of salt rock [22], in this paper, the three-element model for simulating soft tissue viscoelasticity and the nonlinear viscoplastic model are connected in series to form a new model. It includes the description of the plastic deformation process from soft tissue cutting to fracture, which makes the simulation of liver tissue deformation and cutting more accurate, comprehensive, vivid and detailed.

3. Methods

This section mainly introduces the proposed methods. First, we will propose a framework to introduce the modeling expression of the viscoelastic, nonlinear viscoplastic and anisotropic properties of liver tissue, respectively. By combining these biological characteristics with finite element model, the model can simulate more complex deformation behavior of liver tissue. Finally, the design process of the model is summarized in section 3.4, which is related to the update of the node position of the finite element model and the calculation of the feedback force.

3.1. Viscoelastic expression

In reality, soft tissues exhibit hysteresis, relaxation and creep properties, which are collectively referred to as viscoelasticity. Viscoelastic mechanical model can describe the viscoelastic properties of soft tissues. In order to integrate the time-dependent viscous behavior into the complete model, an evolution equation describing the viscous part is usually added to the total strain part, and its solution leads to the update of the viscous stress. Compared with the Kelvin model, which is popular at present, the three-element model is more suitable for simulating the viscoelastic characteristics of liver tissue. It is formed by spring I in series with sticky pot I and then in parallel with spring II. The two springs in the model can be used to represent the linear elastic behavior of liver tissue, and sticky pot can be used to represent the damping characteristics of liver tissue during deformation. Its structure is shown in Fig. 1.

The motion and geometric equations of viscoelastic mechanics are the same as those of elastic mechanics, and the solution of the boundary value can be achieved by solving the motion equation, geometric equation, constitutive equation, initial conditions and boundary conditions [11]. The constitutive equation of the three-element model is shown in Equation (1):

$$E2\varepsilon + (E1 + E2)\tau d\varepsilon / dt = \sigma + \tau d\sigma / dt \tag{1}$$

Where $E1$ and $E2$ respectively represent the stiffness of spring I and spring II, where σ represents stress, $\sigma = \sigma_1 + \sigma_2$, σ_1 and σ_2 are two partial stresses, respectively represent the stress of spring I and sticky pot I in series and the stress of spring II, t represents time, $d\sigma / dt$ is the time derivative of stress, ε represents strain, $d\varepsilon / dt$ is the time derivative of strain, τ represents the creep relaxation time, $\tau = \eta_1 / E1$, and η_1 is the viscosity of sticky pot I in the three-element model. The stress relaxation relation of the three-element model is expressed as Equation (2):

$$\sigma = E2\varepsilon + (\sigma 0 - E2\varepsilon)\exp(-t/\tau) \tag{2}$$

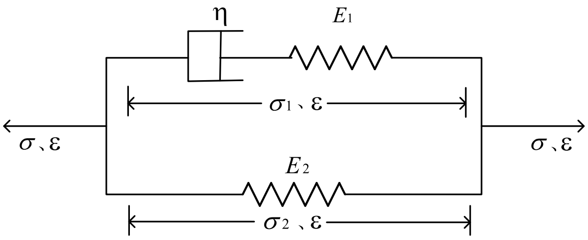


Fig. 1. Three-element model.

where $\sigma 0$ represents the initial stress. The creep equation of the three-element model is expressed as Equation (3):

$$\varepsilon = \sigma / E2 + \sigma(1 / (E1 + E2) - 1 / E2)\exp[-E2t / (E1 + E2)\tau] \tag{3}$$

3.2. Expression of nonlinear viscoplasticity

The three-element viscoelastic model introduced in section 3.1 can describe the creep and hysteresis characteristics of flexible tissues. When considering the virtual surgical deformation of liver, the nonlinear characteristics and viscoplastic deformation of liver should also be taken into account to simulate the viscoplastic deformation process of liver tissue from cutting to fracture.

In the creep process of flexible tissues, the plastic deformation process of creep does exist in biological tissues, but there is a lack of research on the plastic deformation process of flexible tissues [1]. In recent years, based on the indoor triaxial creep compression test, Weimin Han [22] constructed a creep constitutive model that can reflect the nonlinear creep characteristics of salt rock by combining the unsteady generalized Kelvin model and nonlinear Heard. Therefore, in this paper, referring to the classical construction idea of unsteady creep model, we used the three-element model and the nonlinear viscoplastic model in series to take the plastic characteristics into account in the model. The new nonlinear viscoelastic-plastic model constructed is shown in Fig. 2.

When $\sigma \leq \sigma s$, the model degenerates into a three-element model; When $\sigma > \sigma s$, the model is simplified into a nonlinear viscoelastic-plastic model, which is composed of a three-element model and a nonlinear viscoplastic model in series. The creep equation is expressed as Equation (4):

$$\varepsilon = \sigma / E2 + \sigma[1 / (E1 + E2) - 1 / E2]\exp[-E2t / (E1 + E2)\tau] + (\sigma - \sigma s)t^{n}/\eta 2 \tag{4}$$

Where ε represents strain, σ represents stress, $\sigma = \sigma_1 + \sigma_2$, σ_1 and σ_2 are two partial stresses, σ_1 represents the stress of spring I and sticky pot I in series, and σ_2 represents the stress of spring II, $E1$ and $E2$ represent the stiffness of spring I and II, t represents the time, τ represents the creep relaxation time, σs represents the yield limit, $\eta 2$ represents the viscosity of the sticky pot II in the nonlinear viscoplastic model, and n is the creep index of the nonlinear viscoplastic model.

3.3. The expression of anisotropy

Human tissues and organs have obvious anisotropy characteristics. This paper describes the anisotropy characteristics according to Holzapfel and Gasser's method [23]. In this way, the anisotropic hyperelastic behavior of the tissue can be understood as embedding fibers into an isotropic matrix, the overall mechanical behavior is supplemented by fiber reinforced materials. Due to the consideration of fibers, the right Cauchy-Green deformation tensor C introduces the fourth strain invariant $I4$ on the basis of the three main invariants. Therefore, the fourth invariant $I4$ was used in this paper to describe the anisotropic characteristics of liver tissue to reflect the mechanical properties of anisotropic materials, as shown in Equation (5):

$$I4 = a^{T}Ca = 1/2a^{T}F^{T}Fa \tag{5}$$

where, a represents coordinate vectors, a^{T} represents the transposition of coordinate vectors, F represents deformation gradient tensor, F^{T} represents the transposition of deformation gradient tensor.

For each mesh of the model, solve the differential of the strain energy with respect to the vertex, and then obtain the reference shape matrix of the model. By singular value decomposition of the deformation gradient, and then using the additive decomposition of the strain energy function, the anisotropic response corresponding to a certain direction can be included into the model [15]. The strain energy density function $\Psi^{\text{aniso}}(I1,I2,I4)$ of liver tissue with anisotropy can be decomposed as Equation (6):

$$\Psi^{\text{aniso}}(I1,I2,I4) = \Psi^{\text{iso}}(I1,I2) + k1 / k2\left\{exp\left[k2(I4 - 1)^{2}\right] - 1\right\} \tag{6}$$

where $I1$ and $I2$ are the first and second strain tensors of the right Cauchy-Green deformation tensor, $k1$ and $k2$ are material coefficients, and Ψ^{iso} is the strain energy density function of the isotropic material model.

3.4. Model design process

Firstly, we collected the liver data, simplified the sample points and established the background grid, and used the finite element

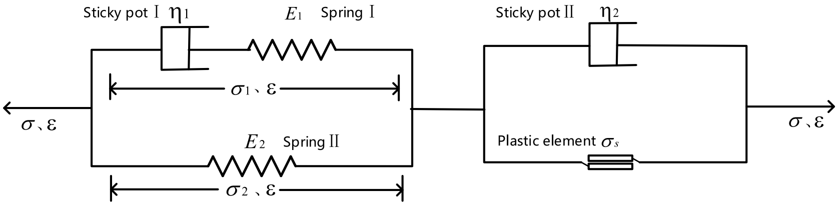


Fig. 2. New nonlinear viscoelastic-plastic model.

model to conduct three-dimensional physical modeling of the liver tissue. In order to better describe the unique biological characteristics of liver tissue, the constitutive model was introduced to express the biological characteristics of liver tissue. The new nonlinear viscoelastic-plastic model was used to express the viscoelastic and nonlinear viscoplastic biological characteristics of liver tissue. When solving the finite element model, the new nonlinear viscoelastic-plastic model is updated by calculating the response of the finite element structure in time and space, updating the stress and strain state variables in the model, and then iterating repeatedly until the required accuracy is achieved. In addition, the fourth invariant of the right Cauchy-Green deformation tensor was used to express the anisotropy of liver tissue. Specifically, the differential of strain energy relative to vertices is solved for each mesh of the finite element model, and the reference shape matrix of the model is obtained. By using the additive decomposition of the strain energy function, the anisotropic response is incorporated into the model. Then, when solving the nonlinear equation derived based on finite element, the

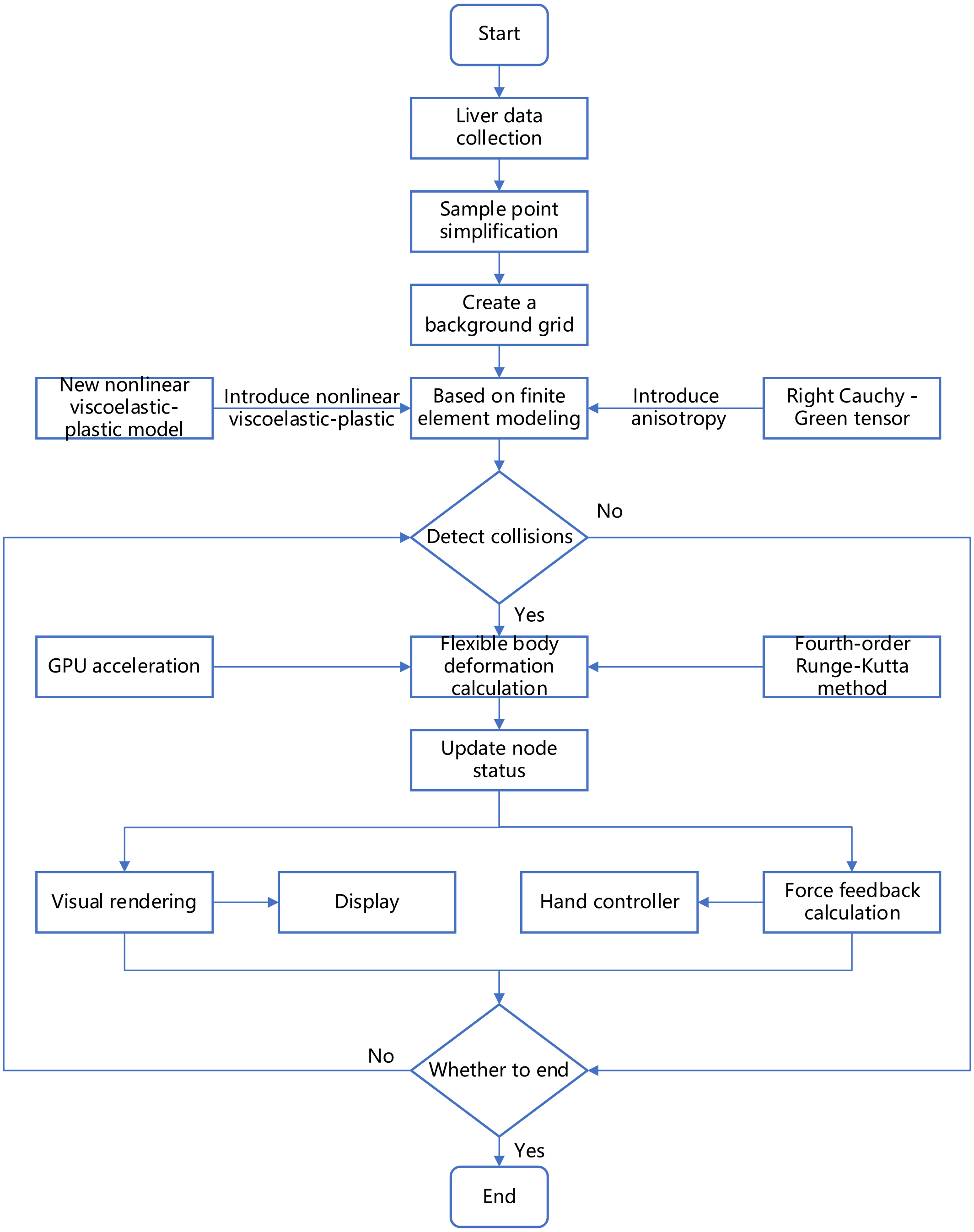


Fig. 3. Flow chart of model design.

fourth-order Runge-Kutta method was used to calculate the deformation of the flexible tissue [9], and the position of the nodes were updated to make the calculation more accurate and efficient. According to the specific parameters of liver, accurate feedback force was calculated. Finally, the PHANTOM OMNI hand controller was operated to sense the feedback force during the operation, in order to verify the effectiveness of the model. The flow chart of model design is shown in Fig. 3.

4. Experiment and results

The experiments verify the accuracy, fidelity and real-time of the model from three aspects. A marked point was taken at the same position in different models, and the varying vertical axial tension was applied to the point. The mechanical test and analysis of the model were carried out, and the displacement of the point at different times was recorded to verify the accuracy of the model. Then, the fidelity of the proposed model was verified by comparing the difference between the applied force and the calculated feedback force, and the deformation and cutting simulation of the liver was carried out. Finally, the deformation and cutting time of different models were compared and analyzed, and the real-time performance of the model was measured by a certain indicator.

4.1. *Environment for the experiment*

The system operates on a private computing machine equipped with an NVIDIA GeForce RTX 2070 series graphics card, an Intel (R) Core (TM) I7-10700 CPU @ 2.90 GHz, 16.0 GB of RAM, and runs on 64-bit Windows 10. The experiment's development environment is based on VC++2021, utilizing the OpenGL4.6 graphical application programming interface, and employing 3DMax2020, equipped with the OpenGL4.6 graphics library as a modeling tool. Furthermore, the force-tactile interaction utilizes the PHANTOM OMNI hand controller, demonstrated in Fig. 4.

4.2. *Verification of accuracy*

In order to verify the accuracy of the proposed model, 5406 tetrahedral units and 1232 nodes were used to construct the liver model. Relevant parameters of human liver tissue were specified to the model, and the mass density was set as 1060 kg/m^3, Young's modular as 3500 Pa, and Poisson's ratio as 0.49 [24,25]. Four models were used to model liver tissue: a new particle spring model that effectively simulates dynamic soft tissue deformation [2], constrained Kalman filter modeling based on finite element method [7], extended Kalman filter nonlinear finite element method for nonlinear soft tissue deformation [12], and proposed model. Take a mark point at the same position of these models, and apply 0–0.63 N vertical axial tension to this point. In order to carry out mechanical test and analysis on the model, the displacement of this point at different times was recorded, as shown in Fig. 5 (a,b). In addition, the relationship between the applied axial pressure and the displacement change ratio of the proposed model was recorded in Fig. 6.

As can be seen from the data obtained in these figures, with the increase of external force, the displacement becomes larger and the creep rate is higher. The simulation results of the proposed model are close to the creep data of other existing models, which means that the proposed model can satisfy the stability and simulation accuracy requirements for non-contact surgery, and validate the model's accuracy.

4.3. *Fidelity verification*

Firstly, the PHANTOM OMNI force feedback haptic instrument was used to interact with the virtual liver model established by the proposed method, and the collision detection between the virtual forceps and the liver tissue was performed. The virtual forceps were used to stretch the proposed liver model to simulate the elastic deformation effect. The pulling force of 0.93 N, 1.65 N, 2.96 N was

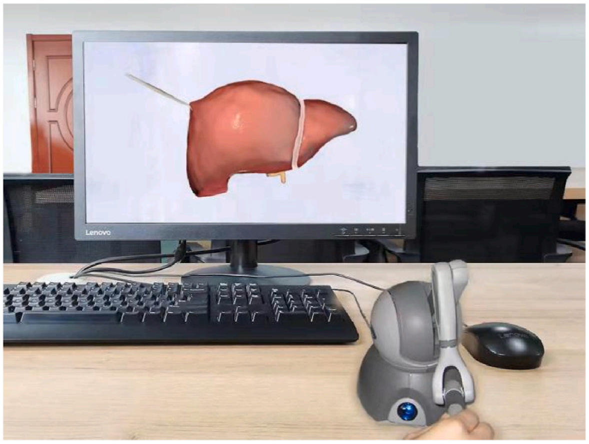
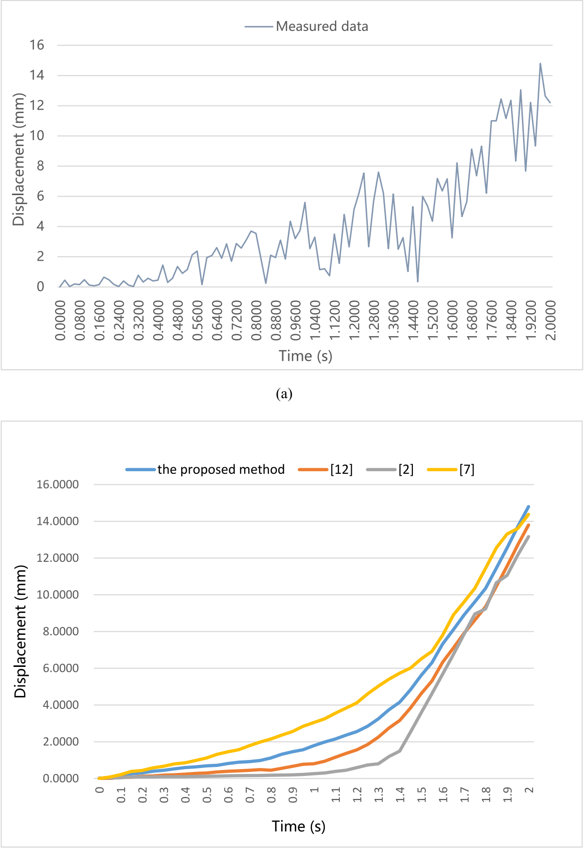


Fig. 4. System diagram of liver surgery.



(a)

(b)

Fig. 5. (a) Measured data; (b)Displacements of four models under different pressures.

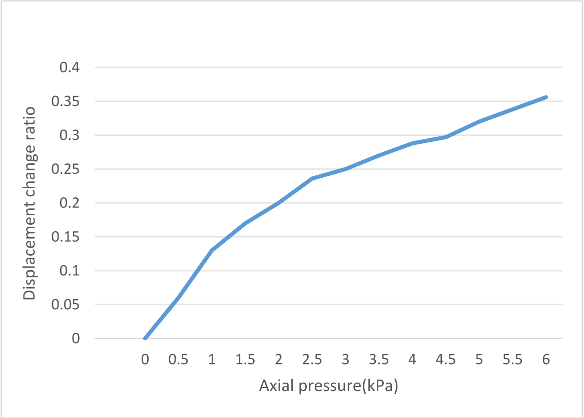


Fig. 6. The relationship between the applied axial pressure and the displacement change ratio.

applied respectively, and the force feedback was calculated, and the difference between the calculated feedback force and the applied force was compared. Due to the effect of external load, with the increase of stress, the simulation scene presented in the surgical simulation was rendered in real time by OpenGL4.6, and the simulation results are illustrated in Fig. 7(a–c).

Fig. 7(a–c) shows the scene of interaction between virtual forceps and virtual liver model. It can be seen from Fig. 7(a–c) that the modeling effect of liver tissue using the proposed model is realistic. With the increase of tension, the deformation effect of virtual liver tissue is vivid, smooth, real and natural, which can vividly show the force displacement relationship of liver tissue, thus verifying the authenticity of the model deformation. In addition, the discrepancy between the applied force and the computed feedback force is negligible and can be disregarded, which demonstrates the stability of the proposed virtual liver model under varying forces. Therefore, the proposed model has realistic deformation effect, accurate feedback force calculation, strong force feedback interaction ability, and can meet the needs of non-contact medical treatment for surgical realism.

Then, a scalpel was used to cut the liver model, and the presented surgical scenes are shown in Fig. 8(a–c).

The experimental results show that the model can not only describe the elastic deformation process, but also realistically simulate the plastic deformation process when the liver model is compressed but does not reach the cutting threshold. Therefore, using this model can obtain realistic visual simulation effects, and can more vividly simulate the whole process of liver model cutting, which can meet the requirements for authenticity of liver virtual surgery in telemedicine.

4.4. Real time verification

Real-time visual feedback can enhance the sense of reality and immersion in virtual surgery, so it is very important to verify the real-time performance of model simulation. In order to verify the computational real-time performance of the proposed model, 3841, 5406, 7312, 9371 and 10583 tetrahedral elements were used to model the liver model. Then, the finite element method using optimized implicit Euler [14], the multi-component conical spring model [3] and the proposed method were used to simulate the deformation and cutting of the virtual liver. And the three models were calculated under $F = 0.75$ N, and the time step was 0.002 s. Table 1 recorded the simulation time for deformation and cutting of liver models with different unit numbers using the three methods. It can be seen from Table 1 that although considering the viscoelastic and other biological characteristics of the model, under the action of external forces, the calculation time of the proposed model is relatively reduced, and the calculation efficiency is better than that of the multi-component conical spring model [3], and it is close to the finite element method using the optimized implicit Euler [14], thus verifying the proposed method's real-time calculation.

Frames Per Second (FPS) represents the number of frames displayed per second, which is an important index to measure the real-time performance of simulation. The higher the FPS, the smoother the dynamic picture and the better the real-time performance of simulation. Therefore, in this paper, FPS value was used to measure the real-time performance of liver deformation simulation. The 3841, 5406, 7312, 9371 and 10583 units were used to model the liver model respectively. Compare the required FPS values of the porous viscoelastic model [13], the fast explicit dynamic finite element algorithm based on transient heat transfer [5], the general cutting fracture model based on Griffith energy [8], a new constrained soft tissue model for interactive surgical simulation [4], a linear iterative boundary reconstruction method [6] and the proposed method when simulating virtual liver tissue. The FPS values of six models based on different number of liver units are shown in Fig. 9. Through the comparison among the six models, the real-time performance of the proposed model was verified.

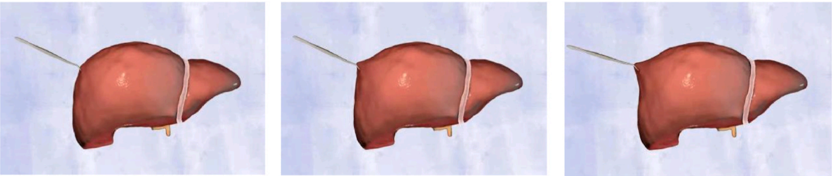
5. Conclusion

Based on the finite element model of the fourth order Runge Kutta method, a high fidelity liver model incorporating biological characteristics was proposed in this paper. When modeling the liver, the complex mechanical behavior and biological characteristics of liver tissue were taken into account in order to address the simulation challenges. The biological characteristics include viscoelasticity, nonlinear viscoplasticity, and anisotropy, which can enhance the accuracy and vividness of the model's deformation and cutting simulation. In addition, because the viscoplastic property was incorporated into the liver model for the first time in this paper, the plastic deformation process of liver tissue before reaching the fracture threshold of cutting surgery can be well simulated, which can better describe the whole process of creep during surgery and improve the fidelity of the model. The experimental results show that the model performs well in accuracy, fidelity and real-time performance. The proposed model can meet the needs of realism in telemedicine, achieve real visual reproduction, and the deformation effect is natural and the simulation is accurate.

The proposed model is more suitable for liver models. In future studies, we aim to utilize the model for experimental analysis on other soft tissue regions of the human body, and try to establish the smoke and blood model during the surgery to enhance the vividness of the simulation process.

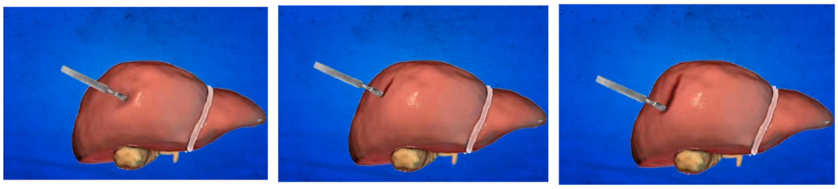
Data availability statement

Data included in article/supplementary material/referenced in article.



(a) 0.93 N (b) 1.65 N (c) 2.96 N

Fig. 7. Several drawing process diagrams of forceps on liver under different forces.



(a) Compression deformation but not reaching the cutting threshold

(b) Cut a small incision

(c) Cut a large incision

Fig. 8. Cutting process charts of liver virtual surgery.

Table 1
Calculation time of soft tissue simulation of different models.

Model Time step (pcs) Number of units (pcs)	[3](Deformation time)	[3](Cutting time)	[14](Deformation time)	[14](Cutting time)	Proposed model (Deformation time)	Proposed model (Cutting time)
3841	452.9	668.3	349.4	789.1	174.5	469.1
5406	681.6	851.2	425.6	993.6	216.9	523.5
7312	829.8	1032.7	501.3	1235.4	323.2	752.9
9371	997.4	1189.3	610.9	1289.2	497.8	918.1
10583	1283.9	1392.5	798.3	1569.8	581.3	997.6

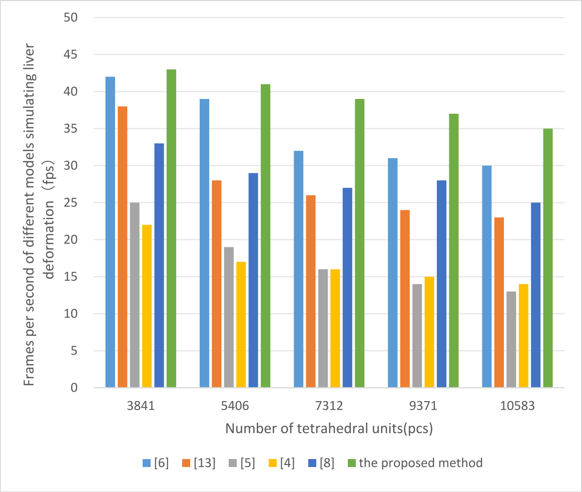


Fig. 9. FPS values of six models based on different number of liver units.

CRediT authorship contribution statement

Xiaorui Zhang: Funding acquisition, Data curation, Conceptualization. **Wenzheng Zhang:** Writing - review & editing, Writing - original draft, Methodology, Investigation, Formal analysis. **Wei Sun:** Software, Project administration, Methodology. **Aiguo Song:** Writing - review & editing, Visualization, Validation. **Tong Xu:** Visualization, Resources, Project administration.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Xiaorui Zhang reports financial support was provided by Natural Science Foundation of Jiangsu Province under grant numbers BK20201136, BK20191401.

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Xiaorui Zhang has patent #2021104164443 issued to Xiaorui Zhang.

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