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Study on Deformation of Vascular Model in Virtual Training System

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***Abstract* - In general, novice physicians need to have simulated training in vascular interventional surgery before surgery. Generally, animal corpses or virtual training systems are used for simulation research. However, the body structure of animal corpses is very different from that of human bodies, so virtual training system is the main research object in recent years. In view of the unreal characteristics of the vascular model of the training system studied in the past, this paper modeled the vascular model on the Unity platform in order to make the virtual training system more immersive, improve the sense of surgical experience of doctors, and increase the sense of presence of doctors during surgery. This paper mainly aims at using the new model in the virtual training system established in the lab when the blood vessel model is a rigid body model when the collision occurs, and the effect of blood vessel deformation is added in the new model, so as to improve the training experience of the virtual training system. The main modeling method adopted in this paper is spring particle model. The results show that the vascular model has good deformation effect and can be adjusted according to the elastic coefficient of different vessels, which can meet the requirements of virtual training system.**

Index Terms - Vascular interventional surgery, virtual, training, Unity, spring-mass

I. Introduction

With the improvement of people's living standard, various diseases come with it. Among them, vascular diseases pose a great threat to people's lives, especially with the increasing aging and urbanization of our country's population, the harm of vascular diseases to people is also increasing[1]. In 2018, the World Health Statistics 2018 of the World Health Organization pointed out that about 17.9 million deaths worldwide were caused by cardiovascular and cerebrovascular diseases, accounting for about 30% of the total number of deaths[2]. Therefore, we can know the threat of cardiovascular and cerebrovascular diseases to human beings, and the treatment of cardiovascular and cerebrovascular diseases is urgent. And the number of patients with cardiovascular disease will continue to increase rapidly in the next 10 years. The increasing burden of cardiovascular diseases has become a major public health problem. China Cardiovascular Disease Report 2018 pointed out that the estimated number of Chinese people suffering from cardiovascular disease is 290 million. Currently, cardiovascular disease is the leading cause of death among urban and rural residents, higher than cancer and other diseases. The mortality rate of cardiovascular diseases in rural areas was 45.50%, and that in urban areas was 43.16%. The mortality rate of cardiovascular diseases in rural areas has been higher than that in urban areas since 2009. This equates to 2 out of every 5 deaths due to cardiovascular disease. The mortality rate of cardiovascular diseases in urban and rural China is shown in Fig.1.

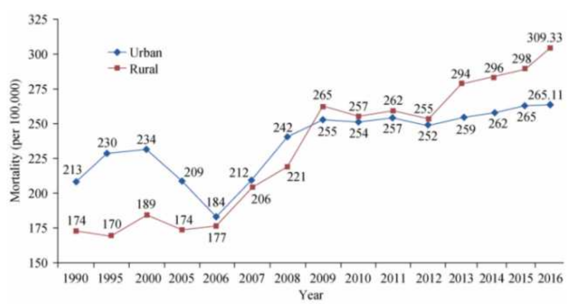


Fig.1 Mortality rates due to cardiovascular disease in urban and rural areas in China: 1990–2016.

At present, the treatment methods for vascular diseases are mainly divided into drug therapy and interventional surgical treatment of two programs. Compared with drug therapy, the method of interventional treatment is aimed at vascular disease is the most direct, the most effective method of minimally invasive vascular interventional surgery is a doctor by catheter forward backward and rotating operation, insert the catheter patients blood vessels, and movement until the lesions of patients in the blood vessels to the treatment of related diseases. Compared with traditional surgery, minimally invasive vascular interventional surgery has been widely used because of its advantages such as less injury, less pain, quick postoperative recovery and so on, which can significantly reduce the pain of patients[3].

In this process, an accurate and objective assessment of surgical skills is essential for good surgical outcomes and safety. During the procedure, the surgeon uses surgical instruments, such as catheters, inserted into the arteries and aortic arcs to rotate, push and pull into the target area. In this process, surgical tools, such as catheters and guidewires, are flexible and miniature. The vascular anatomy is narrow, fragile, and complex, and the visualization of the surgical environment is limited by technical limitations[4]. Therefore, surgical outcome and safety are largely determined by the surgical skill level of the surgeon. Interns often need years of training on animals or cadavers before they can actually go into the operating room. Virtual surgical simulation technology uses computers to simulate real surgical procedures to train medical students and surgeons to improve their operational skills during virtual surgeries without potentially endangering patients' lives. In addition, it can save training time and improve the training efficiency of medical students and surgeons. With the development of virtual surgery technology, people are no longer satisfied with the previous virtual surgery, but pay attention to the authenticity. This article main research content is the authenticity of the research on virtual vascular, we the mass-spring model through the modeling of virtual vascular resolved before the lab angiogenesis collision did not produce deformation defects, improve the authenticity of the virtual surgery, and to a certain extent, can improve the doctor's surgery telepresence.

II. Hardware Platform And Principle

A. *Spring-mass model*

The effect of soft tissue deformation is the key point in the interactive process of virtual surgery. The particle spring model discretizes soft tissue into several grids, and each grid is composed of several particles and several springs. The model can realistically simulate the visual effect of soft tissue deformation[5]. According to topological structure, particle spring model can be divided into surface model and volume model. The surface mass spring model has only surface structure, while the mass point spring model has not only surface structure but also internal structure. Compared with the mass point spring model, the surface mass point spring model has the advantages of simple structure and small calculation cost[6].

B. Theory

In the field of computer graphics, MSM is a general method for modeling variable shapes. For example, dynamic objects such as clothes and hair on the body of animated characters are modeled by MSM to present delicate and realistic changes. MSM is a typical physical approximation model[7]. The system equations are not based on continuous mechanical-physical relations, but on grid topological connections based on spring vibration attenuators. By simplifying the complex partial differential equations under initial conditions and boundary conditions, the computation is reduced and the real-time performance is improved. MSM discretizes a variable form into uniformly distributed nodal elements with mass and position without size, referred to as particles[8].

A spring-particle system is an abstract physical system that assumes that all objects are either particles or springs connected by springs[9]. After such abstraction, to simulate the physical motion of the whole system, it is only necessary to simulate the individual motion of the spring particles and their relations[10]. Particle - spring model is the earliest deformation model based on physical technology, and it is also a relatively classical deformation model. It is composed of the massless spring between the particles and the particles dispersed by the physical properties of the whole deformed object, so that the mass of the object is concentrated in each particle and the overall energy of the model system tends to zero energy.

a) Structural spring:

Structural spring is connected between two adjacent particles in the horizontal and vertical aspects of the spring, the role of the spring is to maintain the size of the tension between adjacent particles, play a role of fixing the original model.

b) Twisted spring:

Twisted springs are also called shear springs. Different from the structural spring, the two adjacent points connected by the torsion spring are two adjacent particles at opposite angles, which plays a role in preventing the object from twisting and deforming. Since the structural spring can only hold the basic shape of the object, without the twisting spring, when the object is distorted, the object will look like a two-dimensional object, which cannot produce good results.

c) Stretch the spring:

A stretch spring is also called a bend spring. To connect the longitudinal and transverse aspects of a particle, note that it must be two particles separated by a particle. The function of the spring is to make the deformation of the object more smooth.

C. *Modeling platform*

Unity is the platform we use for the simulation of the training system. Unity3D is a comprehensive multi-platform game development tool developed by Unity Technologies that allows you to easily create interactive content such as 3D video games, architectural visualization, real-time 3D animation and so on. It is a comprehensive integrated professional game engine. Compared to other platforms, such as VTK and openCL, Unity has the following features[11]:

1.visual programming interface to complete various development work, efficient script editing, convenient development;

2.automatic instant import, Unity supports most 3D models, bones and animation directly import, map material automatically converted to U3D format;

3. Multi-platform development and deployment of works can be completed with one click;

4.the bottom support OpenGL and Direct11, simple and practical physics engine, high-quality particle system, easy to use, realistic effect;

5. support Java Script, C#, Boo Script language;

6.Unity has excellent performance, outstanding development efficiency and cost-effective advantages.

III. Spring-particle model

The geometric model used in the laboratory has two advantages of verisimilitude and high efficiency. I mainly carry out research on vascular physical modeling based on this geometric model. We have put forward based on the theory of particle spring flexible vascular surface model, mainly aimed at the current virtual vascular interventional surgery of the defects in the system, the blood vessels as a rigid body to simulate the interventional procedure, rigid blood vessels do not have soft tissue features, greatly reduces the immersive training doctor's surgery. As a classical theory, mass spring has been widely used in soft tissue modeling[12].

A. Hooke's law

The particle - spring model is to regularly discrete objects into many particles, particles connected by springs. The particles in the model are artificially assumed to have mass and the mass of the whole object is evenly distributed to each particle. The particles are connected by a virtual spring, a retractable spring with linear elasticity that obeys Hooke's Law.

Hooke's Law：

$$F = -kx \tag{3.1}$$

Where F represents the size of the force, K represents the stiffness coefficient of the object, and X represents the type variable of the object. Hooke's law of elasticity points out: spring in elastic deformation, spring elasticity and spring elongation (or compression) is proportional to the elastic coefficient of the material, it is only determined by the nature of the material, and other factors have nothing to do. The minus sign indicates that the spring is exerting force in the opposite direction of its extension (or compression).

The formula in Hooke's Law is as follows:

$$f_{a,b} = -k_s \frac{x_a - x_b}{\| x_a - x_b \|}(\| x_a - x_b \| - l) \tag{3.2}$$

Where x_a and x_b respectively represent the positions of the two ends of the spring, l representing the original length of the spring. In parentheses are the shape variables of the spring under force, corresponding to x in Hooke's law. $\frac{x_a - x_b}{\| x_a - x_b \|}$ represents the direction of force on the spring.

B. Damping

In order to better describe the viscoelastic biomechanical properties such as creep of soft tissue model, the damping force that hinders the current particle movement should be properly considered while considering the spring force:

$$f = -kv \tag{3.3}$$

Where k is the damping coefficient of the spring and V is the velocity of the particle, as shown in Fig.2. As mentioned earlier, the mass-spring model based on the soft tissue in by force, force and spring between the elastic and damping force, etc.), under the action of change makes the position of the particle, thus further update vertex positions on the geometric model of soft tissue, realize human tissue under the action of external force deformation simulation[13].

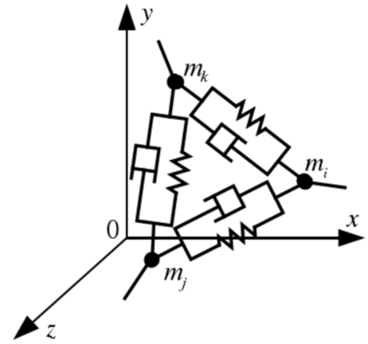


Fig.2 The model of mass-spring-damper

In our above spring model, the damping of the spring can be expressed by the following formula:

$$f_{a,b} = -k_d \frac{x_a - x_b}{\| x_a - x_b \|}(v_b - v_a) \cdot \frac{x_a - x_b}{\| x_a - x_b \|} \tag{3.4}$$

Which k_d represents the stiffness coefficient of the spring, v_a and v_b respectively represents the velocity of the particle at both ends of the spring.

In the mass-spring model, the role of the damper is to reduce the system instability caused by the excessive oscillation of the particle caused by the external force and the spring elasticity. The magnitude of the damping force is directly related to the velocity of the particle, that is, the faster the particle moves, the greater the damping force of the spring attached to the particle.

C. Force analysis of particle

In the mass-spring model system, the internal force of the particle is more complicated than the external force. On the one hand, it is affected by the spring force, on the other hand, it is also affected by the damping force of the damper. According to Hooke's law, t $F = m\ddot{x} + d\dot{x} + kx$ he force on a single particle can be obtained:

$$ma = F_i - F_k - F_d \tag{3.5}$$

Where m represents the mass of the particle, a represents the acceleration of the particle at this time, F_i is the resultant force of external forces on the particle, F_k and F_d respectively represents the elastic force and damping force of the spring connected to the current particle.

At any time t in the process of soft tissue model deformation simulation, the deformation of human soft tissue model can be described by differential equation.Therefore, the above equation can be expressed as:

$$F = m\ddot{x} + d\dot{x} + kx \tag{3.6}$$

This is x represented by distance, $\dot{x}$ by velocity, and $\ddot{x}$ by acceleration.

D. Explicit Euler

For graphic rendering of virtual surgical system, visual refresh frequency is required to be above 30HZ [14]at least to ensure continuous visual rendering effect. In the virtual surgical system based on the mass-spring model, the time step of deformation simulation directly determines the real-time performance of the virtual surgical system, and selecting an appropriate time step is a necessary prerequisite to ensure the accuracy and real-time performance of soft tissue deformation in the virtual surgical system. Explicit Euler method a commonly used numerical product decomposition method[15].

The Explicit Euler integral is the simplest numerical method for solving ordinary differential equations. Its equations are:

$$\begin{cases} v(t) = v_0 + \int_{t_0}^{t} f(t)/m dt \\ x(t) = x_0 + \int_{t_0}^{t} v(t) dt \end{cases} \tag{3.7}$$

And satisfy the initial condition $v(t_0) = v_0$, $v(t_0) = v_0$.

IV.MODEL STRUCTURES

The above part is just the basic principle of spring-particle model. The next important thing is to build the vascular model in Unity platform, and study the spring-particle deformation according to the existing vascular model. What we use here is the virtual vascular model of surface drawing.

In the study of soft tissue deformation, the stiffness coefficient of spring is the most important factor for spring mass model. In elasticity, Young's modulus is the proportional constant between the longitudinal stress and the longitudinal strain of soft tissue, which reflects the degree of difficulty of object deformation. Poisson's ratio refers to the ratio of transverse strain to longitudinal strain in the proportional limit of elastomer material, which reflects the elastic constant of transverse deformation of elastomer[16]. In general, young's modulus E and Poisson's ratio of soft tissue range from 0 to 15K and 0 to 0.5[17], respectively.The solution formula of elastic modulus is as follows:

$$E = \frac{\sigma}{\varepsilon} = \frac{F/A}{(h-h_0)/h_0} \tag{4.1}$$

Where F is the size of the external force on the object, A is the size of the cross-sectional area of the measured object, h_0 is the size of the original height of the object, h is the height of the object under force.

Hooke's law is important in the model of spring particles. According to Hooke's law, within the elastic limit of an object, stress and stress become proportional, and its proportional coefficient is called Young's modulus. The relationship between Hooke's law and Young's modulus is:

$$k = E\frac{A}{h_0} \tag{4.2}$$

Where, E is the young's modulus of the object, A is the force area of the circular surface of the blood vessel, and h_0 is the original height of the blood vessel.

Limited by the lack of tools to measure the vascular coefficient in the laboratory, we used the research of Wang Bin et al.[18], Hebei University, and obtained the young's modulus of blood vessels is $E = 14.24KPa$, and the elastic coefficient is . $k = 41.106$

V .EXPERIMENTS AND RESULTS

A. The experimental set up

We read the existing vascular source file in STL format on unity platform.According to the stiffness coefficient obtained before, we built a vascular model in Unity, and conducted collision experiments in Unity to test the shape variables.

Because what we want to achieve is compression and depression deformation of the vascular model. This requires pushing all vertices near the contact point into the surface. However, if the external force we apply does not specify an internal direction, it will apply equally in all directions. This causes the vertices in the plane to be pushed around rather than in. To achieve the inward direction of the force along the point of contact, we can add a direction. A slight offset ensures that vertices are always pushed into the surface. The normal line at the contact point can be used as the offset direction. We obtain the offset direction by calculating the normal of the triangle on the vascular model

We added collision detection model to the established vascular model to detect collision events of blood vessels. When we move the rigid body model in Unity to make the object collide, the blood vessel detects the collision event and produces the corresponding deformation.The experimental process is show in Fig.3.

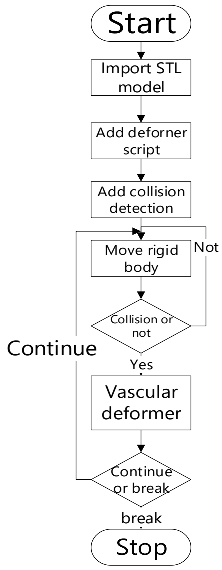
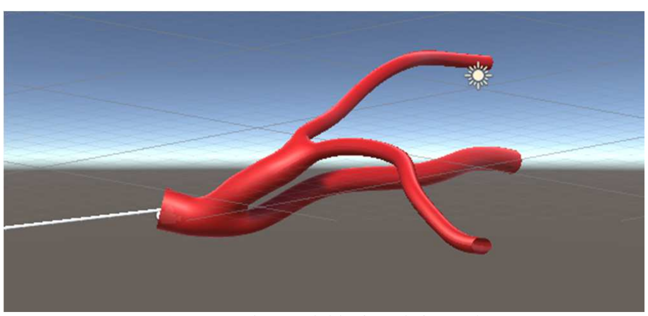


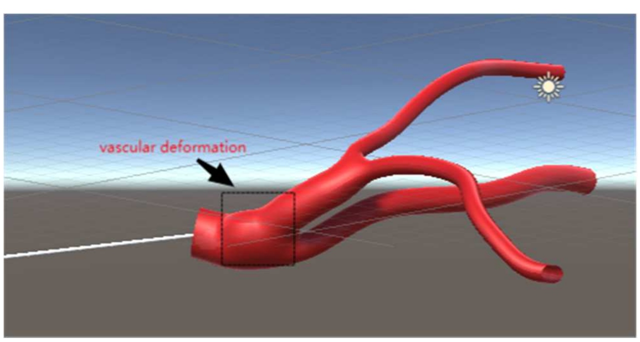
Fig.3 Experimental process

B. Experimental Result and analysis

We conduct demonstration operations on the model in Unity, as shown in Fig.4 a) is the vascular model without transformation, and Fig.4 b) is the vascular model after transformation.



a) Vascular model before deformation



b) Vascular model after deformation

Fig.4 Effect before and after vascular deformation

From the Fig above, we can see that obvious deformation occurs when the blood vessel is stressed, which proves that our model is a working model.

We extracted the size of the form variable in a period of time, and calculated the deformation under the corresponding force according to Hooke's law. The results are shown in Fig. 5.

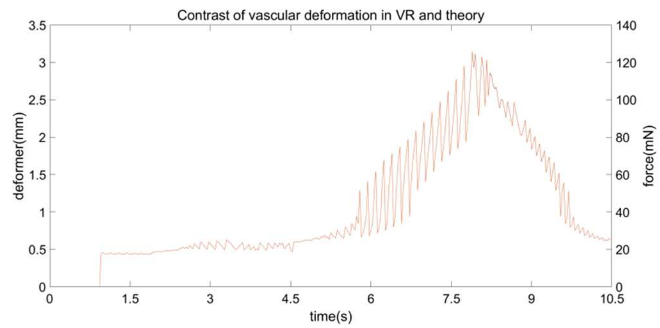


Fig.5 Comparison of simulated and theoretical variables

It can be seen from the above figure that the error between the theoretical shape variable and the simulation shape variable is less than 3.5mm.The left axis is the shape variable(mm) and the right axis is the applied force(mN).According to the study, when the vascular force is less than 120mN[19], the vessel will not be punctured, so this study can meet the needs.The error is shown in the Fig.6.

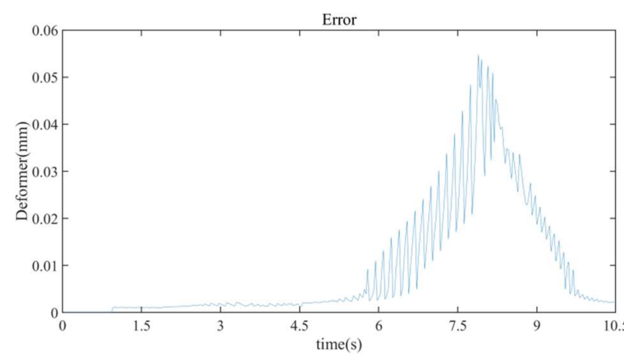


Fig.6 Error of deformation in VR and theory

We seen the above Fig.The force size is within 140mN, and the maximum error is not more than 0.06mm.Because the maximum error is less than 0.1mm, it is difficult to be detected by human eyes[20].

In order to see the effect of spring mass model more intuitively. According to the above error chart, we conducted further data analysis on the error data.The error analysis is shown in Fig.7.

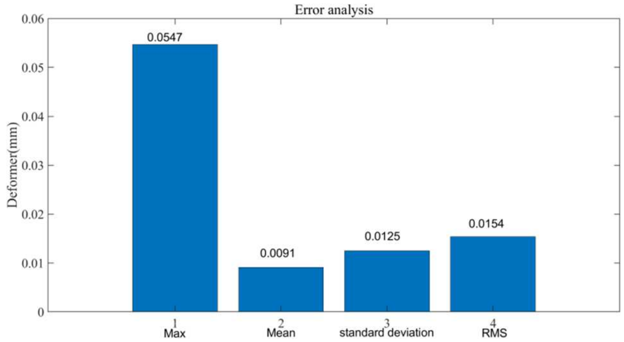


Fig.7 Error Analysis

After experiments, we found that when the force within 140mN was generated, the size of the shape variable of the model was within 3.5mm, and the maximum error was less than 0.06mm compared with the shape variable derived from the formula.The average error is 0.0091mm,the Standard deviation is 0.0125mm, The smaller the standard deviation, the less these values deviate from the mean, and vice versa. The size of the standard deviation can be measured by multiplying the standard deviation with the mean.They mean that the error is about the average error.The RMS is 0.0154 mm. The root mean square error is used to measure the deviation between the observed value and the true value.The smaller its value is, the closer the theoretical value is to the real value.Studies have shown that when the shape variable is less than 0.1mm, the human eye will not detect a significant difference. So the experimental results show that the model can meet the experimental requirements.

VI .CONCLUSION

In this paper, the problem of non-deformation of blood vessels in the virtual training system of vascular interventional surgery was studied, and the spring particle model was adopted to deal with the deformation. Experiments show that the spring particle model can deal with the deformation of the object well. Since vascular deformation is a small-scale deformation process, the spring particle model can meet our experimental requirements.

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