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Virtual brain surgery simulation system based on haptic interaction①

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Abstract

To improve the accuracy and interactivity of soft tissue deformation simulation, a new plate spring model based on physics is proposed. The model is parameterized and thus can be adapted to simulate different organs. Different soft tissues are modeled by changing the width, number of pieces, thickness, and length of a single plate spring. In this paper, the structural design, calculation of soft tissue deformation and real-time feedback operations of our system are also introduced. To evaluate the feasibility of the system and validate the model, an experimental system of haptic interaction, in which users can use virtual hands to pull virtual brain tissues, is built using PHANTOM OMNI devices. Experimental results show that the proposed system is stable, accurate and promising for modeling instantaneous soft tissue deformation.

Key words: haptic feedback, human-computer interaction, surgery simulation, soft tissue deformation

0 Introduction

In virtual reality medical applications, haptic feedback systems can break the isolation between the real world and the virtual world. They provide an augmented environment for doctors to interact with simulated tissues much as they do with real tissues. Haptic feedback systems make it possible to build an accurate, reliable, and flexible training system. Simulating surgical procedures with such systems before performing real surgery increases the safety of the surgery and may reduce the surgery duration. Moreover, through repeated trials in the virtual surgery, an optimal solution could be found to make patients receive minimal trauma.

Brain surgery deals with the most complex and delicate organs of a human body. The complexity and multiplicity of life and cognitive functions of the brain make brain surgery very difficult. A brain surgery simulation system based on virtual reality and haptic interaction could effectively reduce training costs and improve the success rate of brain surgery. This study proposes and describes such a system based on virtual reality and two PHANTOM OMNI haptic interaction devices. The system simulates the deformation in brain tissues caused by pulling forces from virtual operations.

1 System platform

Fig. 1 shows the prototype virtual brain surgery simulation system supporting haptic interaction.

1.1 Hardware components

The system is built on a computer with Intel Core2 Duo CPU, 4.00GHz, 4.00GB RAM, and graphics card HD5750. With the joysticks of the PHANTOM OMNI haptic devices, operators are able to control a pair

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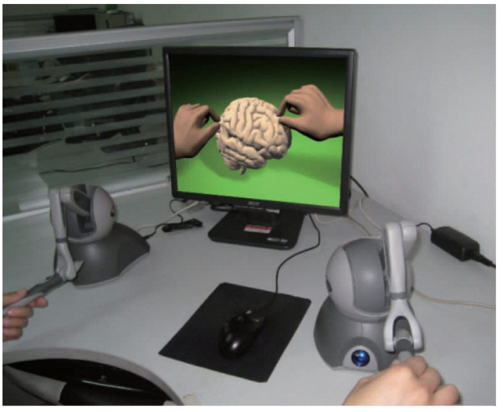


Fig. 1 Surgery simulation system

of virtual hands to touch the virtual brain and sense feedback forces. The PHANTOM OMNI working space is 16 × 12 × 7cm, which equals the space where a person's wrist and forearm can move and bend freely. The displacement accuracy is 0.055mm, and the maximum force is 3.3N.

1.2 Software components

The models of the virtual hands and the virtual soft tissue are built using 3DS MAX 2013, OpenGL, and Microsoft Visual C + + 2012.

2 Key technologies of virtual surgery simulation

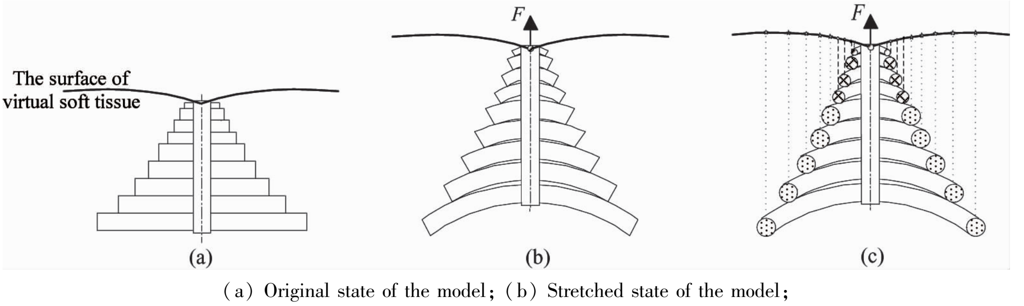
A simple and accurate model that presents efficiently the deformation and haptic characteristics of a real organ is the key of virtual surgery simulation[1]. The quality of the physical model built directly determines the accuracy and speed of the virtual surgery simulation.

2.1 Modeling the object

Among all popular methods of modeling soft tissues, finite element models[2-5] have the advantages in high modeling precision and adjustable parameters. However, deformation modeling is complex due to expensive computation. Mass-spring models[6-11] can be quickly computed and easily implemented, and thus can be better adapted to changes in soft tissue structures. However, due to the limitations of mechanical structure, this model presents difficulties in building a system model, determining parameter values and measuring the accuracy of simulation results. Boundary element models[12] can reduce the dimension of the problem and simplify the calculation by focusing on the model boundary, but it is still challenging to make the model stable. The Long element model[13] is a highly simplified model. Although it is easy to compute, its high abstraction leads to a lower level of accuracy. The layered rhombus-chain-connected model[14] is convenient and fast to calculate, and can satisfy real-time requirements due to its simple nature. However, distortions are prone to occur at the boundary of the soft tissue because each layer of the model is composed of an identical rhombus chain structural unit. These conventional modeling methods suffer from either problems of complicated calculations or low simulation accuracy. It is still challenging to make a virtual surgery system satisfy requirements of reality, stability and real-time performance.

2.2 Modeling the interaction between a virtual agent and soft tissues

When the system detects that the virtual hands touch the surface of the virtual soft tissues, the local contact area will be filled with a virtual plate spring model with a given virtual tension F. During the virtual hand and tissue interaction, the output feedback under the given tension is calculated by using the virtual plate spring model, which can then be used for the real-time haptic portrayal of any virtual soft tissue deformation. The structure of the virtual plate spring model is shown in Fig. 2.



(a) Original state of the model; (b) Stretched state of the model;
(c) Corresponding relationship between the surface of virtual soft tissue and different layers

Fig. 2 Virtual plate spring deformation model

The proposed modeling method is as follows:

(1) Parameters are initialized;

(2) Under the given virtual contact tension F, when the virtual agent hits any point on the surface of the virtual soft tissue, the plate springs in the first layer will be placed under the collision point. Suppose the number of plate springs in the first layer is n_1: $n_1 = 1$. Let the width of the plate spring be b, its thickness be h_1, and its length be l_1. The plate springs in the second layer are placed under the first layer, and the second layer consists of n_2 pieces of plate springs, $n_2 = 3$: their width is b, thickness is h_2, $h_2 = h_1\alpha$, and lengths are l_1q, l_1q^2, and l_1q^3, respectively. The plate springs in the third layer are placed under the second layer. The third layer has n_3 pieces of plate springs, $n_3 = 5$; their width is b, thickness is h_3, $h_3 = h_1\alpha^2$, and lengths are l_1q^4, l_1q^5, l_1q^6, l_1q^7, and l_1q^8, respectively. The rest of the layers can be calculated analogously. Specifically, the plate springs in the i-th layer are placed under the $(i-1)$-th layer. The i-th layer has n_i pieces of plate springs, their width is b, thickness is h_i, $h_i = h_1\alpha^{i-1}$, and length is $l_1q^{(i-1)^2}$, $l_1q^{(i-1)^2+1}$, $l_1q^{(i-1)^2+2}$,…… and $l_1q^{i^2-1}$ respectively. n_i represents the number of the plate springs in the i-th layer, where $n_i = 2i - 1$, $i = 1,2,3,\cdots\cdots N$, N is the number of layers. The thickness of the plate spring in each layer constitutes a geometric sequence whose first term is h_1 and common ratio is α, where $\alpha \in [1, 2]$. The length of plate springs in each layer constitutes a geometric sequence whose first term is l_1, and common ratio is q, where $q \in [1, 1.5]$. All the plate springs are clamped together using a spring hoop whose width is B, and $b \leqslant B \leqslant b + 0.1$.

When the plate springs are clamped, there will be an invalid part in all the plate springs in the haptic virtual model, which should be considered and properly corrected in calculating the spring stiffness. Assuming that all the n_i plate springs in the i-th layer have the same stiffness, the equivalent spring stiffness $\tilde{P}_i$ after correction is given by

$$\tilde{P}_i = \left(\frac{2L'_i}{2L'_i - 0.6B}\right)^3 \cdot P_i \tag{1}$$

where the equivalent length L'_i of n_i plate springs in the i-th layer can be expressed by

$$L'_i = \frac{l_1q^{(i-1)^2} + l_1q^{(i-1)^2+1} + l_1q^{(i-1)^2+2} + \cdots\cdots + l_1q^{i^2-1}}{n_i} = \frac{l_1q^{(i-1)^2} + l_1q^{(i-1)^2+1} + l_1q^{(i-1)^2+2} + \cdots\cdots + l_1q^{i^2-1}}{2i-1} \tag{2}$$

The equivalent spring stiffness P_i of n_i plate springs in the i-th layer, without considering the invalid part, is given by

$$P_i = \frac{3EI'_i}{L'^3_i} \tag{3}$$

where E is the elastic modulus. The equivalent sectional moment of inertia I'_i of n_i plate springs in the i-th layer can be written as

$$I'_i = \frac{bH'^3_i}{12} \tag{4}$$

The equivalent thickness H'_i of n_i plate springs in the i-th layer is given by

$$H'_i = h_i = h_1\alpha^{i-1} \tag{5}$$

Assuming that the action line of the given virtual contact tension F is the same as the center line of the virtual plate spring model producing the haptic force, and under the effect of the given virtual contact tension F, if M layers of plate springs in the virtual soft tissue model are deformed, then the M-th layer is called deformation cutoff layer (DCL).

Suppose that the given virtual contact tension F can make the deformation X_1 reach its given deflection value X_{C1}, where X_1 is generated when n_1 plate spring is stretched in the first layer. In this case, we assume that the deformation caused by all plate springs in the first $M-1$ layers is the same as the deflection given in the first layer, and the deformation amount produced by any plate spring is not greater than the deflection X_{C1} given in the first layer when n_M plate springs in the M-th layer named DCL are stretched simultaneously.

Force F_1 is given by Eq. (6) when n_1 plate spring in the first layer is stretched:

$$F_1 = \begin{cases} X_{C1} \cdot \tilde{P}_1 & i = M > 1 \quad \text{the } M\text{-}th \text{ layer is DCL} \\ F & i = M = 1 \quad \text{the } 1\text{-}th \text{ layer is DCL} \end{cases} \tag{6}$$

According to Eq. (1), the equivalent spring stiffness $\tilde{P}_1$ of the plate spring in the first layer after correction is given by

$$\tilde{P}_1 = \left(\frac{2L'_1}{2L'_1 - 0.6B}\right)^3 \cdot P_1 \tag{7}$$

According to Eqs(3,4), one can get the equivalent spring stiffness P_1 of the plate spring in the first layer without considering the invalid part, and the equivalent sectional moment of inertia I'_1 of the plate spring in the first layer.

According to Eq. (5), the equivalent thickness H'_1 of the plate spring in the first layer can be expressed as

$$H'_1 = h_1 \tag{8}$$

Except for the first layer and the M-th layer named DCL, the tension F_j consumed is given when n_j

plate springs in the j-th layer are stretched simultaneously:

$$F_j = \frac{48E \cdot I'_j \cdot X_{C1}}{\delta \cdot L'^3_j} \tag{9}$$

where $j \in [2, M-1]$, and j is an integer.

According to Eq. (4), the equivalent sectional moment of inertia I'_j of the plate springs in the j layer can be got.

Based on Eq. (5), the equivalent thickness H'_j of the plate springs in the j-th layer can be expressed as

$$H'_j = h_j = h_1 \alpha^{j-1} \tag{10}$$

According to Eq. (2), the equivalent length L'_j of the plate springs in the j-th layer can be expressed as

$$L'_j = \frac{l_1 q^{(j-1)^2} + l_1 q^{(j-1)^2+1} + l_1 q^{(j-1)^2+2} + \cdots\cdots + l_1 q^{j^2-1}}{n_j} = \frac{l_1 q^{(j-1)^2} + l_1 q^{(j-1)^2+1} + l_1 q^{(j-1)^2+2} + \cdots\cdots + l_1 q^{j^2-1}}{2j-1} \tag{11}$$

The sum X_M of the deformation is produced when n_M plate springs in the M-th layer named DCL are stretched simultaneously. It is given by

$$X_M = \frac{F - \sum_{i=1}^{M-1} F_i}{\tilde{P}_M} \tag{12}$$

The deformation $\bar{X}_M$ produced by any plate spring is given by when n_M plate springs in the DCL are stretched simultaneously:

$$\bar{X}_M = \frac{X_M}{n_M} = \frac{X_M}{2M-1} \tag{13}$$

In line with Eq. (1), the equivalent spring stiffness $\tilde{P}_M$ of $n_M = 2M-1$ plate springs in the cutoff layer after correction is given by

$$\tilde{P}_M = \left(\frac{2L'_M}{2L'_M - 0.6B}\right)^3 \cdot P_M \tag{14}$$

According to Eq. (2), the equivalent length L'_M of n_M plate springs in the DCL is given by

$$L'_M = \frac{l_1 q^{(M-1)^2} + l_1 q^{(M-1)^2+1} + l_1 q^{(M-1)^2+2} + \cdots\cdots + l_1 q^{M^2-1}}{n_M} = \frac{l_1 q^{(M-1)^2} + l_1 q^{(M-1)^2+1} + l_1 q^{(M-1)^2+2} + \cdots\cdots + l_1 q^{M^2-1}}{2M-1} \tag{15}$$

According to Eqs(3,4), one can get the equivalent spring stiffness P_M of n_M plate springs in the DCL without considering the invalid part and the equivalent sectional moment of inertia I'_M of n_M plate springs in the DCL.

Based on Eq. (5), the equivalent thickness H'_M of n_M plate springs in the M-th layer can be expressed as

$$H'_M = h_M = h_1 \alpha^{M-1} \tag{16}$$

Let t_i indicate the delay time demanded for the stretch of plate springs in the i-th layer, and T_i denotes the sum of delay time required when all plate springs are stretched in the first i layers. The delay time t_i of every layer forms a geometric sequence headed by the delay time t_1 required when the plate spring in the first layer is stretched with ω as the common ratio:

$$t_i = \omega^{i-1} t_1 \tag{17}$$

The calculation begins when the virtual agent contacts the surface of soft tissues, and it is assumed that the total delay time T_i should meet $T_i < T$ when all the plate springs in the first i layers are stretched, where T is the reciprocal of the refresh rate of haptic force production.

$$T_i = t_1 + t_2 + t_3 + \cdots + t_{i-1} + t_i = \frac{1-\omega^i}{1-\omega} \cdot t_1 \tag{18}$$

The sum of the deformation of all plate springs used in the virtual haptic model can be regarded as the deformation of the virtual soft tissues. Let X denote the sum of the deformation produced when all the plate springs in the first M layers are stretched, X_i indicates the sum of the deformation produced when n_i plate springs in the i-th layer ($i < M$) are stretched simultaneously, and X_M denotes the sum of the deformation when n_M plate springs in DCL are stretched simultaneously.

$$X = \begin{cases} \sum_{i=1}^{M-1} X_i + X_M = \sum_{i=1}^{M-1} n_i \cdot X_{C1} + X_M \\ \qquad = \sum_{i=1}^{M-1} (2i-1) \cdot X_{C1} + X_M \\ \qquad i = M > 1 \text{ the } M\text{-}th \text{ layer is the DCL} \\ \dfrac{F}{\tilde{P}_1} \qquad i = M = 1 \text{ the first layer is the DCL} \end{cases} \tag{19}$$

2.3 Deformation simulation process

The haptic interactive virtual surgery simulation system is established using the driver GHOST SDK (General Haptics Open Software Toolkit Software Development Kit), which supports PHANTOM OMNI devices. The specific process of real-time simulation is shown in Fig. 3.

3 Experiments and Results

In order to evaluate the reality and stability of the proposed haptic system, 35 candidates are invited to participate in the experiment. The age of 35 candidates are ranged from 22 to 28, and the average age is 24.5. Before the experiment, each candidate experiences the sense of touch for 5 minutes in the virtual brain simulation systems to learn the virtual environment.

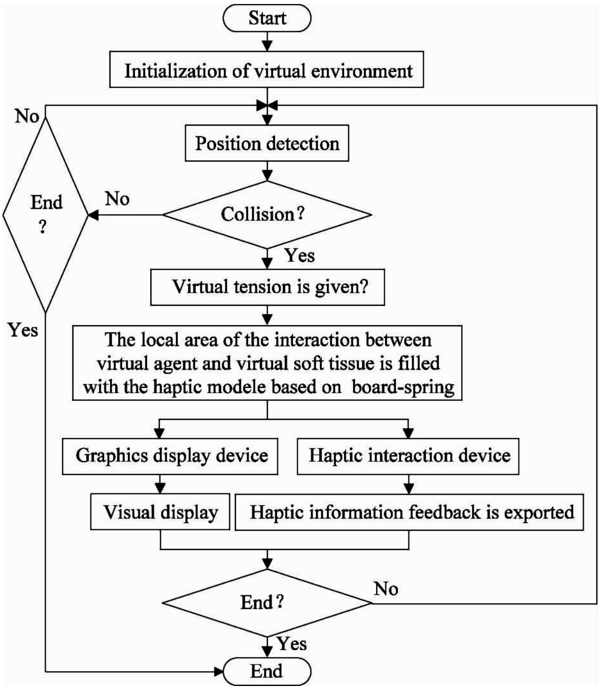


Fig. 3 Flow chart

3.1 Verification of simulation

During the experiment, as shown in Fig. 4, the participants are asked to pull the soft tissue along the surface of the brain and give their evaluation of system performance. During the interaction, all the candidates

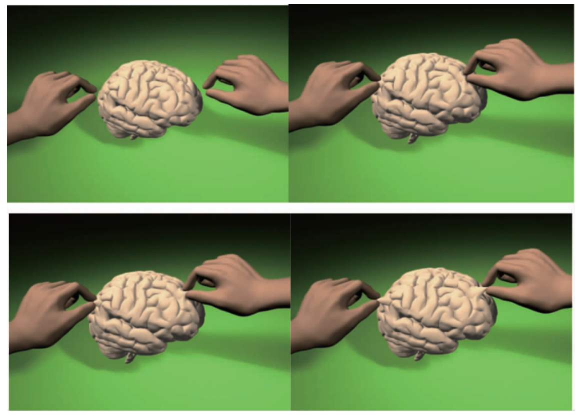


Fig. 4 Simulation progress of virtual hands pulling on virtual brain tissues

can naturally feel the fine haptic information between the virtual hands and the virtual brain tissues.

The experimental results show that the proposed model has some advantages, compared with the classical finite element model[15] and mass-spring model[16]. The contents and a comparison of results of the perception experiments are shown in Table 1. So the established interactive system based on the plate spring model can effectively and naturally simulate the deformation when soft tissues are stretched under the action of the force.

During the actual interaction between haptic device and virtual object, image display is smooth and non-stop, haptic-force sense is also stable, and the simulation result is realistic. From the haptic experimental results, It is verified that the proposed method does not produce any vibration or unstable forces in haptic interaction.

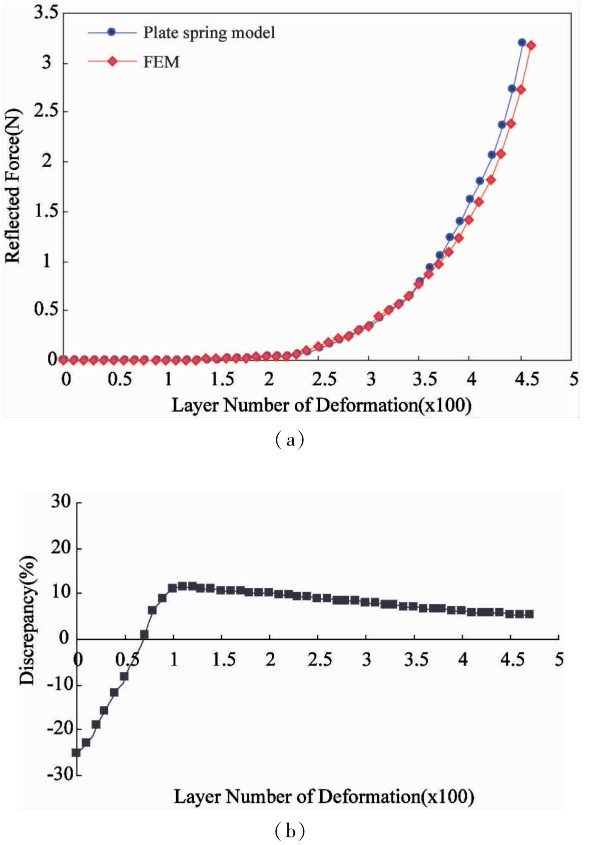
Table 1 Comparison results of perception experiments

Contents of perception experiment	Finite element model			Mass-spring model			Model proposed		
	Yes /A	No /A	Favorable rate	Yes /A	No /A	Favorable rate	Yes /A	No /A	Favorable rate
Is interaction real and natural?	25	10	71.4%	27	8	77.1%	29	6	82.9%
Does interactive process meet people's behavior?	24	11	68.6%	28	7	80%	30	5	85.7%
Does the interaction reflect the texture feature of organs?	26	9	74.3%	23	12	65.7%	28	7	80%
Is the interaction comfortable?	27	8	77.1%	26	9	74.3%	31	4	88.6%
Can it guide interoperate?	23	12	65.7%	24	11	68.6%	28	7	80%
Is the interaction real-time?	22	13	62.9%	24	11	8.6%	29	6	82.9%
Is feedback information true?	28	7	80%	25	10	71.4%	31	4	88.6%
Are deformation effects realistic?	20	15	57.1%	26	9	74.3%	28	7	80%
Is the system stable?	27	8	77.1%	28	7	80%	32	3	91.4%
Time needed for real-time deformation of model/ms (Fig. 4)	21.35			23.08			14.69		

3.2 Physical behavior analysis

Generally, the FEM model can provide more excellent performance for object modeling than the other models. Hence, the haptic behavior of our model is compared with that of the FEM[17]. In the study, plotted the feedback force for the objects modeled is plotted with FEM and the plate spring model, respectively.

The haptic rendering cannot satisfy real-time requirement by FEM model because of the computational burden. Fig. 5(a) shows the haptic results of the brain tissues modeled with FEM and the plate spring model. As can be seen, the haptic behavior of the plate spring model follows better than that of FEM, so our proposed model can provide stable force to users without vibration.



(a)

(b)

Fig. 5 Haptic results of the FEM and the plate spring model

In order to verify the validity of the plate spring model, the discrepancy of the plate spring is calculated on the basis of the FEM value. The differential threshold for the force that the human can reliably discriminate is about 10% over the force range of 0.5 ~ 200N, for the force smaller than 0.5N, the threshold increases to 25%. From Fig. 5(b), it can be seen that the difference between the feedback force based on the plate spring model and that based on FEM is smaller than the differential threshold for force that the user can reliably discriminate. Hence, our plate spring model can not only simulate the deformation of soft objects in real time but also provide a realistic feeling to users.

4 Conclusions

According to the requirements of real-time human-computer interaction of haptic system for soft tissue simulation, a virtual plate spring model is proposed in this paper. Thus, a virtual brain surgery simulation system is built using PHANTOM OMNI haptic interaction devices, realizing the deformation simulation of virtual hands pulling the brain tissues. Compared with other commonly used haptic models, it is real-time, realistic and quick in computation. Haptic perception experiments indicate that the system can provide users a vivid and efficient operation experience.

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