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Soft Tissue Modeling using Nonlinear Mass Spring and Simplified Medial Representation

Feng Chen, Lixu Gu*, Pengfei Huang, Jingsi Zhang and Jianrong Xu*

Abstract—In this paper, we present a novel approach for real-time simulation of deformable soft tissue. When using Mass-Spring or Finite Element Method to simulate the global deformation of soft tissue dynamically, we'll meet the difficulty that the size of the 3D problem (the number of elements in the Mass-Spring or FEM mesh) is much larger than the 2D issue. So we put forward a hybrid model to solve the problems. This model consists of a deformable centerline and surface reconstruction mechanism based on simplified medial-representation algorithm and nonlinear mass-spring model, and we also proposed the local deformation method so that the accuracy is achieved and real-time requirement is also satisfied. We use a segmented left kidney and blood vessel as the examples in our case study.

I. INTRODUCTION

VIRTUAL Surgery Simulation is devoted to simulate operation of various phenomena that may be encountered in the course of the virtual reality applications. The study involved computer graphics, computer vision, elasticity, biomechanics, robotics, medicine and many other fields. Through knowledge in the field of the above target we can implement the geometric model, physics model of organ, collision detection, real-time deformation (response, fracture), surgical photorealistic rendering and other functions. Among them, geometric modeling and physics modeling are the basis for calculation. And the geometric modeling, graphics rendering, collision detection is the classic computer graphics and image processing, have accumulated a lot of results and experiences. However, because of the interdisciplinary characteristics, the physical and geometric modeling of soft tissues and organs for human in virtual surgery research and application are relatively backward. And the research and application of this kind of system has become a bottleneck.

In the virtual surgery simulation system, there are normally physical model of linear elastic model and nonlinear model. Finite Element Method (FEM) is famous for accuracy and stability [1-2], but it is time-consuming and difficult to implement. Mass-Spring systems are fast when the number of nodes is relatively small [3-4], while its stability depends on the value of parameters, and the traditional Mass-Spring system does not represent the inner structure appropriately, which results in the unreasonable appearance under large

scale force. M-Rep's modeling of the global deformation is effective, because of the skeleton structure [5-7], but the modeling of the surface might be rough. The novel approach proposed in this paper addresses the problems mentioned above by introducing Nonlinear Mass-Spring System and a hybrid model integrating the advantages of Medial Representation and Mass-Spring. In order to improve the efficiency and accuracy, we also propose a Simplified Medial Representation Method (SMRM). Specifically, we introduce a novel concept of Deformable Centerline and use it as the Medial Structure to model the global deformation based on SMRM. Then we add the surface local deformation, which is based on local FEM, onto the global deformation to make it more accurate.

The paper is organized as follow. In section 2, we provide a Mass-Spring structure with skeleton. Then in section 3, we propose a simplified medial representation model and nonlinear mass-spring concept. The local deformation using simplified local FEM calculation will also be covered in section 4. All the experiments will be discussed in section 5.

II. MASS-SPRING DEFORMATION WITH CENTERLINE

Mass-Spring is to model the soft tissue into a number of discrete masses, and connect these mass points with springs. The deformation of objects is expressed through the compression and tensile between springs [8]. The springs' topology used here is based on Balloon Segmentation, which means that each mass connects with its six neighboring points through springs, as showed in Fig.1.
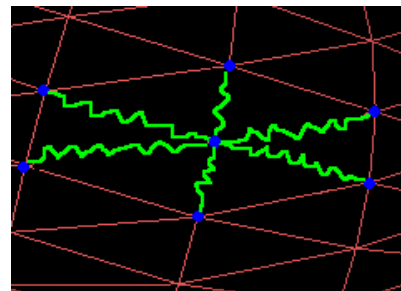

Fig. 1 the springs' layout of the surface mode

Spring is a fundamental unit in Mass-Spring model. Fig.2 presents two essential parts of the unit: the elastic equipment and the damper [2]. The former generates elasticity force proportional to the alteration of the springs' length, and the latter engenders damping force proportional to the velocity of mass-points.

In the dynamic Mass-Spring system, at any given time t, the equilibrium equation has the following form:

$$m_i \times a_i(t) + d_i \times v_i(t) + \sum_{j \subset \sigma(i)}(k_{i,j} \times \Delta L_{i,j}) = F_i \qquad (1)$$

In this equation, m_i, d_i, and F_i represent the mass, damping factor and external force of the point i respectively, $a_i(t)$ and $v_i(t)$ represent the acceleration and velocity at time t respectively, $k_{i,j}$ represents the stiffness of the spring between point i and j, $\Delta L_{i,j}$ represents the length alternation of the spring linking point i and j, $\sigma(i)$ represents the mass points directly linking to the point i. So $\sum_{j \subset \sigma(i)}(k_{i,j} \times \Delta L_{i,j})$ represents all the spring forces on point i from the 6 neighbor spring.
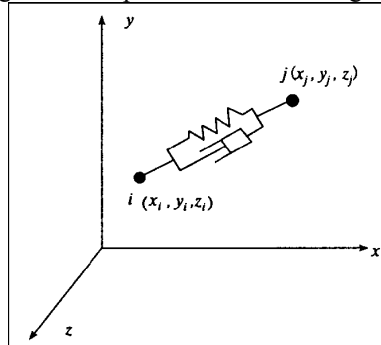

Fig. 2 the basic component of Mass Spring system: masses (black spots), damper (the rectangular) and spring

In the implementation, in order to prevent soft tissue from escaping from the original location, we induct a concept of fixed position [6]. Here, we presume that each point has a corresponding fixed spot located in the original position of the point, and the point connects with the spot through springs named return-springs. As a result, soft tissue always has a tendency to go back to the original position. For example, *P1P1'*, *P2P2'*, *P3P3'* and *P4P4'* are the return-springs whose initial length is zero in Fig. 3.
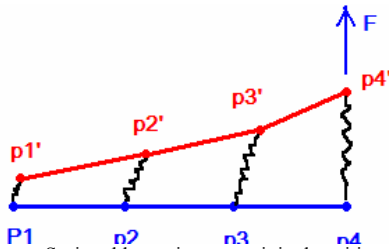

Fig.3 the Return-Spring, blue points are original positions, red points are current positions

S.M. Pizer introduced a deformable model (M-Rep) which uses medial atoms and a particular tuple ($\{x, r, F(b, n), \theta\}$) [6] to imply the boundary coordinates of soft-tissue. M-Rep is a sound approach to reflect the internal information because each medial atom represents an interior section [9,10] of the object. In the system the Distance Mapping Method [12] is employed to extract the skeleton, along which media atoms are selected evenly and automatically. In our kidney case, a skeleton structure is introduced. The surface Mass Spring system and the skeleton topology are combined to spawn a hybrid elastic model. Each spoke will be linked with the nearest boundary points.

III. SURFACE RECONSTRUCTION WITH SIMPLIFIED MEDIAL REPRESENTATION

A. Traditional Medial Representation

Medial Representation algorithm is a model based on Centerline. It records information of the centerline atoms only. When there is a deformation on the centerline, we can redraw the object's surface through the centerline information. So Medial Representation is quite appropriate to model soft tissue like blood vessel.

In our model, the centerline is modeled into a Mass-Spring system. That is, each two neighbor atoms on the centerline are linked by a spring, as Fig.4 shows. When a force is added on the centerline, it'll deform like any mass-spring system. Then we accordingly alternate the surface mesh points to reconstruct the entire mesh rendering.
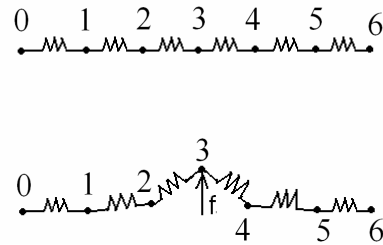

Fig.4 Mass-Spring centerline

Due to the efficiency priority to the accuracy in simulation, the original Medial Representation method is simplified as hubs and spokes structure to sacrifice accuracy for speed.

Traditionally, on the basis of Blum's medial axes and from Medial Representation, Prizer proposed the M-Rep method, which is excellent to represent the internal structure and uses medial atoms and a particular tuple $\{x, r, F(\bar{b}, \bar{n}), \theta\}$ to indicate the boundary of the deformable object [4, 5] (as shown in Fig.5).
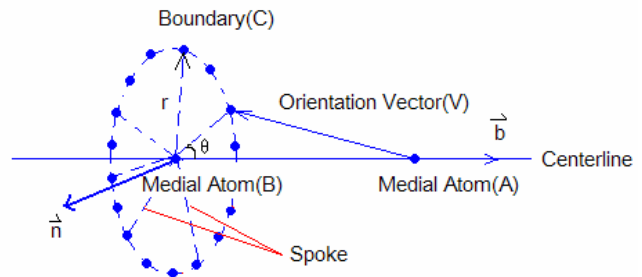

Fig.5 traditional medial representation structure

In traditional M-Rep method, to draw the whole surface, calculate every boundary node by the following formula:

$$C = x + R_{V,AB}(\theta)(\overrightarrow{AB} \bullet \overrightarrow{r_{BC}})/|AB|. \qquad (2)$$

Where C and x are the coordinates of boundary C and medial atom B respectively; R denotes the operator to rotate its operand by the argument angle in the plane spanned by V and AB; |AB| means the length of the vector AB. Other spokes connecting with B can be calculated by rotating BC around BA and scale the r length. Iterating the process can obtain all boundaries. So we can get the whole surface.

B. Simplified Medial Representation

Here, we modified the implement method of the M-Rep algorithm a little to simplify the model. That is, we don't use the concept of Orientation Vector, but the method as follows.

For atom i (i=2,3…n-1) on the centerline, the first boundary node B of this atom can be anyone(usually we choose the one that on the plane xOy of Cartesian coordinates) that satisfies the formula:

$$\begin{cases} \overrightarrow{C_{i-1}C_{i+1}} \bullet \overrightarrow{C_iB} = 0 \\ |C_iB| = r \end{cases} \quad (3)$$

Where C_i means the ith atom on the centerline. That is, C_iB must be vertical to vector $C_{i-1}C_{i+1}$, and have the length of r. Then calculate every boundary node, use the following formula:

$$B' = x + R_{C_{i-1}C_{i+1}}(\theta)B/|r|. \quad (4)$$

R denotes the operator to rotate its operand by the argument angle θ with the axis represented by the vector $C_{i-1}C_{i+1}$, B' and x are the coordinates of boundary and medial atom C_i respectively. The method is showed in Fig.6.

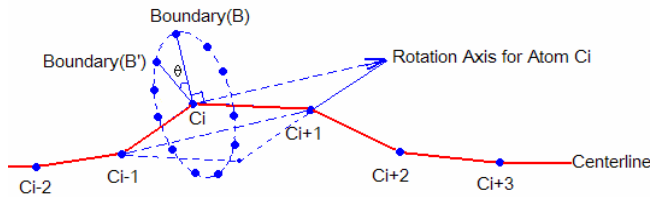Fig.6 surface reconstruction method of simplified M-Rep (the red line is the centerline)

C. Nonlinear Mass-Spring

Strictly speaking, all the systems in reality are nonlinear systems. Linear systems are only to make it simpler for mathematical treat and to derive an idealized model. [11]

Due to the physical properties of soft tissue, the use of linear spring deformation may lead to some distortion of the result. To solve this problem, we introduced the concept of nonlinear spring system. That means the internal force is no longer a linear term of nodal displacements, as showed in Fig.7.
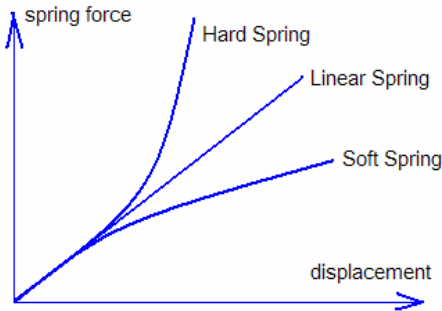

Fig.7 nonlinear spring

There are many kinds of nonlinear method in calculating the deformation. However, Mass-Spring is quite different from FEM. Accuracy based on simplicity and real-time request is our goal. So we introduce the following Duffing's equation:

$$m_i \times a_i(t) + d_i \times v_i(t) + \sum_{j \subset \sigma(i)}(k_{i,j} \times \Delta L_{i,j} + k'_{i,j} \times \Delta L^3_{i,j}) = F_i$$

(5)

Here, $k_{i,j} \times \Delta L_{i,j} + k'_{i,j} \times \Delta L^3_{i,j}$ represents the nonlinear spring force. When $k'_{i,j} > 0$, the spring is so-called Hard Spring system, and when $k'_{i,j} < 0$, it's Soft Spring system. Considering our soft tissue characteristics, Hard Spring system is chosen for our vessel case. As for the value of k', it depends on the characteristics of the object to model. In our case, we use $k' = \frac{1}{100}k$, which makes the simulation better.

Although the simplified Medial Presentation works pretty well for global deformation, the accuracy around the point on which force is added still needs some improvement.

To solve this problem, we introduce a local deformation hybrid model. That is, calculate the local deformation of the area around the node on which the force is added. Then add the local deformation to the global deformation. We use a static FEM equation:

$$KU = F \quad (6)$$

Where U is the vector of nodal displacements, F represents the applied external force, and K is the stiffness matrix of the system. For example, we can choose 25 nodes, centered by the node on which the external force is added, as showed in Fig.8.
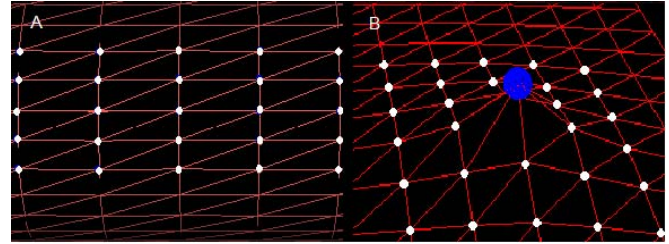

Fig.8 local deformation (white points are the nodes chosen to calculate in (6), B shows the result when all the points are on a plane)

As for the stiffness matrix K, assemble it like this:
(1) K is 3n order matrix (n is the number of nodes chosen);
(2) Initial K=**0**;
(3) If node i and j are linked by a spring, assemble K like this: K_{ii}+=kx, $K_{i+1,i+1}$+=ky, $K_{i+2,i+2}$+=kz, K_{jj}+=kx, $K_{j+1,j+1}$+=ky, $K_{j+2,Kj+2}$+=kz, K_{ij}-=kx, $K_{j+1,j+1}$-=ky, $K_{j+2,j+2}$-=kz, K_{ji}-=kx, $K_{j+1,j+1}$-=ky, $K_{j+2,j+2}$-=kz, which is called superposition method; kx, ky and kz represent the three weights on Cartesian coordinate system of k respectively.

F is a 3n-dimensional vector. If a force f= (fx, fy, fz) is added on node i, set F_i= fx, F_{i+1}=fy, F_{i+2}=fz. And as for the boundary condition such as you want to set certain nodes remain static, for example, the node i, set $\sum_{j=1}^{3n}K_{ij} = 0$, $\sum_{j=1}^{3n}K_{i+1,j} = 0$,

$\sum_{j=1}^{3n}K_{i+2,j} = 0$ and set K_{ii}=1, $K_{i+1,i+1}$=1, $K_{i+2,i+2}$=1. Solve this equation to get every node's displacement.

IV. EXPERIMENTS

All the experiments are done in a computer with 2.6GHz Pentium IV CPU, 1GB DDR2 memory and NVIDIA Geforce5200 graphic card.

In our first experiment, we use Mass-Spring with centerline skeleton to model a kidney. There are 458 masses on the surface and 42 on the centerline. The k' in (5) is set 0.01*k. First, we add a force on the surface. Then we release the force and check out its behavior. The result is showed in Fig.9.
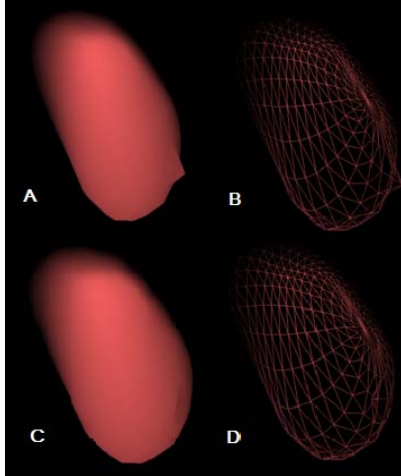

Fig.9 Mass-Spring deformation based on a kidney case (A,B: add a force on the surface. C,D: release the force)
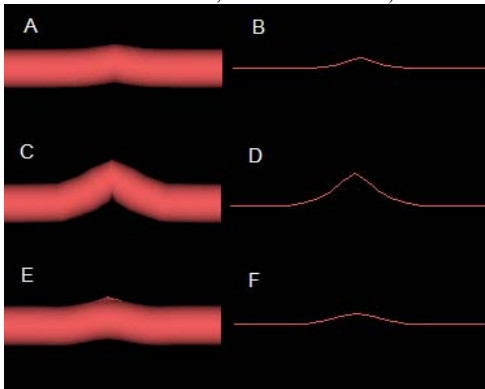

Fig.10 nonlinear Medial-Representation in our vessel case (A,B shows small deformation, C,D shows large deformation, E,F shows small deformation with surface local deformation)

Then we use our simplified Medial Representation with nonlinear mass-spring centerline to simulate human blood vessel deformation. In our experiment, there are 40 atoms on the centerline and 30 spokes for each centerline atoms. So there are 1200 nodes on the surface in total. The k' in (5) is set 0.01*k. To check out the global deformation, we add a lighter force and a stronger force respectively. The result is showed in Fig.10. The computation time is showed in TABLE I. TABLE II shows the situation including local deformation.

TABLE I
COMPUTATION TIME (SECONDS) FOR DIFFERENT MODEL PER UPDATE

	Mass-Spring Model	Simplified Medial Presentation
Linear	0.018	0.013
Nonlinear	0.022	0.016

TABLE II
COMPUTATION TIME (SECONDS) WITH AND WITHOUT LOCAL DEFORMATION (WITH NONLINEAR MASS-SPRING) PER UPDATE

	Mass-Spring Model	Simplified Medial Presentation
Without Local Deformation	0.022	0.016
With Local Deformation	0.032	0.027

V. CONCLUSION

From our experiments, we can see that our hybrid model works well. And compare with FEM, the model is much simpler, and the calculating is much faster, and at the same time the deformation is realistic. The introduced nonlinear mass-spring system formula (5) doesn't affect the calculating speed a lot, but the object deformation behavior is more realistic. Both the accuracy and real-time requirement are satisfied. And our future work is to model more complicated soft tissue such as blood vessel with branches. In order to obtain the branches of the complex soft-tissue, our simplified Medial Representation algorithm needs to be improved.

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