Real-Time Simulation for Global Deformation of Soft Tissue Using Deformable Centerline and Medial Representation

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Abstract. Real-time simulation for global deformation of soft tissue, using Mass-Spring or traditional finite element method (FEM), is difficult because of the following reasons: (1) The linear elastic model is inappropriate for simulating large deformation for the probably unreasonable distortion; (2) The size of the 3D problem (the number of elements in the Mass-Spring or FEM mesh) is much larger than a 2D issue. In this paper, we propose a novel approach for these 2 problems: (1) deploying a deformable centerline, combined with medial representation method instead of the traditional linear elastic model, to simulate large motion and global deformation of a 3D tube like object; (2) applying a simplified algorithm which reconstructs the soft tissue surface by the medial representation method and reduces the complexity of a 3D problem.

1 Introduction

The simulation of human soft tissue has a long history in biomedical engineering and computer science. Nowadays, aiming to achieve virtual reality, the real-time requirement of simulation has been considered as the key part.

In the recent decades, simulations for local deformation of 3D objects can yield plausible results by using FEM or Mass-Spring [1, 2]. Local deformation means the deformation which is limited in a relatively small region of the object, like poking, nipping, pressing, and cutting. Besides small alternation of an object, we may also want to simulate the large scale deforming. However, as far as the global deformation is concerned, we can hardly find the solution by simply using FEM due to its expensive computational cost or Mass-Spring because of its inaccuracy, so that an efficient and accurate deformable modeling method for the simulation is still under further research.

Global deformation is commonly happened in medical domain and worth simulating for virtual surgery. We could take the human intestine as a good example for this case: while observing the patience's intestine, it is inevitable that the patience

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will move and so will his/her intestine move dynamically. In this situation, which is different from the other soft tissue's minor deformations like needle insertion, scalpel cutting or forceps nipping, the intestine will move globally. Zhuang proposed a non-linear FEM model to simulate the global deformation of object [3], but it is difficult to implement and expensive in computation.

Medial Representation was proposed to use Medial Structure to represent the deformation of an object [4, 5]. The traditional Medial Representation method costs too much computation so that, to improve the efficiency, we propose a Simplified Medial Representation Method (SMRM). Specifically, in this paper, we introduce a novel concept of Deformable Centerline and use it as the Medial Structure to model the global deformation based on SMRM.

Our work is distinguished from many other previous works by the following two aspects: 1) simulation on global deformation of tube like organ rather than the local deformation; 2) simulation based on the dynamic performance instead of static performance of the deformation.

In section 2, we would propose a brand new model of Deformable Centerline. Then in section 3, we would simplify the traditional Medial Representation method to simulate the global deformation in a real-time manner. At last, we would illustrate our experimental results and draw our conclusion.

2 Deformable Centerline Modeling Based on Mass-Spring

The notion of centerline was first proposed by Blum [4]. Intuitively, a centerline of a soft tissue is a central path which traverses that organ. However, some soft tissues may have complex structures, such as the human heart, so they have several branches connecting to the centerline or to each other through the organ and forming a skeleton [6]. In this paper, we use the term of centerline and our model will be principally based upon it. In the model, a fast and automatic centerline extraction algorithm was employed based on a Distance Mapping Method [7].

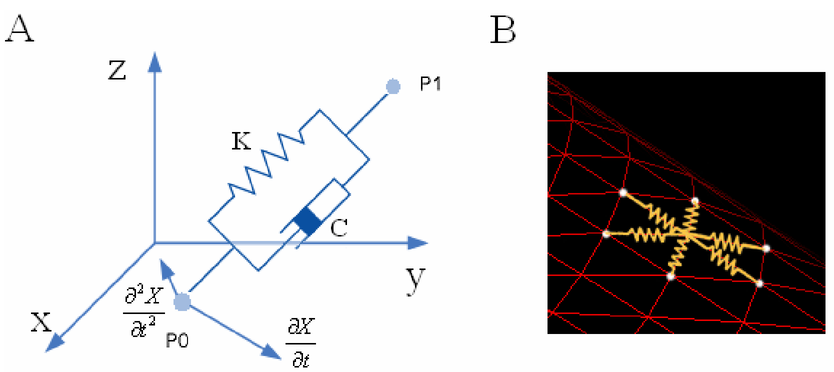

Fig. 1. (A) The spring element in 3D Mass-Spring system. (B) The Spring Mesh Structure.

2.1 Mass-Spring Model

The Mass-Spring system is a physical based technique that has been widely and efficiently used to model deformable objects [2]. A non-rigid object is modeled as a collection of point masses linked by springs in a mesh structure.

Mass-Spring is especially effective in simulating the dynamic behavior of the objects; however, it is innately unsuitable to simulate the static behavior due to its unstable vibration among the spring system and the shape distortions of the topology [8]. To reduce vibration and improve stability of the deformable model, damping factor and non-linear elasticity methods are used. In the dynamic Mass-Spring system, the equilibrium equation has the following form:

$$M\frac{\partial^2 X}{\partial t^2} + D\frac{\partial X}{\partial t} + KX = F(X) \tag{1}$$

where $\frac{\partial X}{\partial t}$ and $\frac{\partial^2 X}{\partial t^2}$ are the first and second derivatives of x with respect to time, M is the mass matrix, D the damping factor matrix, and K the stiffness matrix. F denotes the external forces. Equation (1) defines a coupled system of 3n ordinary differential equations for the n position vectors contained in X. To solve them, we could transfer equation (1) into a coupled system of linear equations based on Euler's first order method.

2.2 Centerline Modeling

After the extraction, the centerline is modeled to a Mass-Spring system, a set of points that are averagely distributed along its backbone and linked with springs by each two points in order of (Fig. 2 (A)). When a dynamic force is applied, a deformation bended reasonably and smoothly enough is expected (Fig. 2 (B)).

Mass-Spring system has the deficiency that the mass points and spring links are over discretized [7]. While the force is applying on one point, its propagation is not simultaneous. Therefore, an unexpected peak will occur, and the cause of this problem is the lack of upward forces on the neighbor points (Fig. 2 (C)).

To conquer the problems described above, we propose a novel method to model the deformation of the centerline.

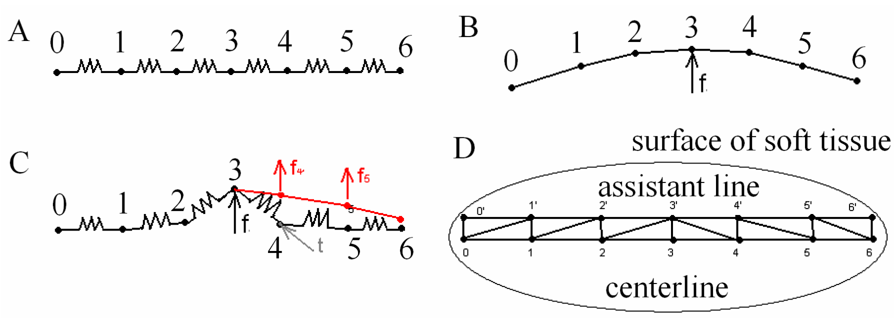

Fig. 2. (A) Mass-Spring Centerline. (B) Desirable Deformation Result. (C) Factual Deformation Result. (D) The Extended Mesh.

A dynamic offset line as an Assistant Line (AL) is constructed from the original centerline to refine the model composition and approximate the deformation.

To compensate the upward forces, tractive springs are designed and the extended mesh is established by the following steps: (1) Offset the centerline (P_0, P_1, …, P_n) in the direction of the applied force as the AL (P_0', P_1', …, P_n'); (2) Link the corresponding points of two lines, P_0 with P_0', P_1 with P_1', etc; (3) Given the force applying on P_k, link P_k' with P_{k+1}, P_{k+1}' with P_{k+2}, etc, and link P_k' with P_{k-1}, P_{k-1}', with P_{k-2}, etc, as the tractive springs.

Under the assistance of AL, the force applied on P3 will propagate orderly through P_2, P_1, and P_0 on the left side, P_4, P_5, and P_6 on the right side, yielding the desirable result described above (as shown in Fig. 3).

Moreover, in our model, it is assumed that the human soft tissue is attached to several fixed points, therefore they would return to the original position after motion or deformation via returning springs [9]. As a result, the deformable centerline always tends to return back to the original position as a stable status. To refine the model, angular spring is employed to simulate bending under the curvature force [10].

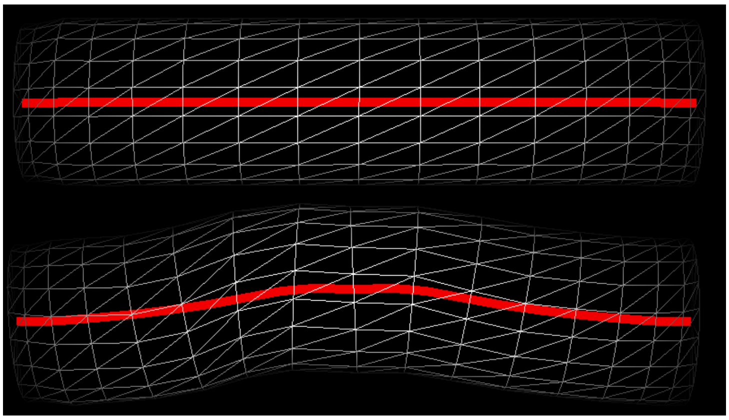

Fig. 3. Centerline Deformation Result Based on Mass-Spring with the Extended Mesh

3 Simplified Medial Representation Method

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 $\{x, r, F(\vec{b}, \vec{n}), \theta\}$ to indicate the boundary of the deformable object [4, 5] (as shown in Fig. 4 (A)).

Traditionally, Medial Representation is used for registration and segmentation, but here we employ it for modeling the global deformation of human soft tissue which is similar to the bending of mitochondria and blood vessel. In the proposed simplified model, the Medial Representation method is adapted to a deformable model by deforming the centerline in advance and then accordingly alternating the surface mesh points to reconstruct the entire mesh rendering.

3.1 The Hubs and Spokes Structure

Due to the efficiency priority to the accuracy in simulation, the original Medial Representation method is simplified as hubs and spokes structure (as shown in Fig. 4 (B)) to sacrifice accuracy for speed. The medial atoms and tuples are refined as hubs and spokes, which imply the boundary information of the deformable object, to reduce the complexity of the method. The atoms are viewed as hubs, and spokes shoot out from them equally. In the simplified structure, one tuple is related to one spoke, containing less information, and spokes have various length, whereas in traditional Medial Representation such as M-Rep, each tuple is for each medial atom and radius is constant.

A novel method is proposed to calculate the static boundary *C*, and the tuple is reset to $\{x, r, F(V, \overline{AB}), \theta\}$ [9]. In the tuple, x is the position of the atom B; r denotes the radius of the spoke $\overline{BC}$; F represents the plane determined by vector *V*, called Orientation Vector of boundary orienting from *A* to *C*, and centerline segment $\overline{AB}$; the angle between a spoke $\overline{BC}$ and the centerline section $\overline{AB}$ is constant as θ.

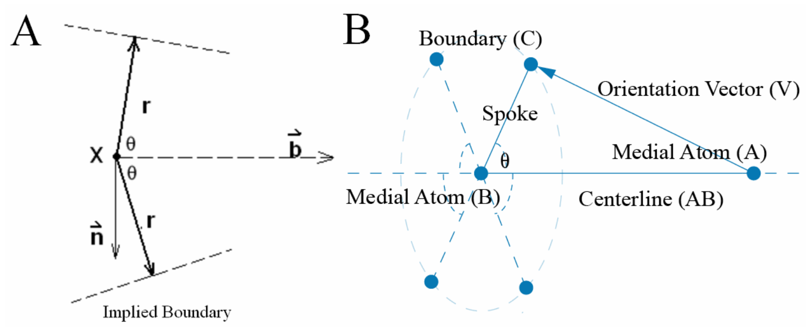

Fig. 4. (A) Medial Atom Tuple in Medial Representation. (B) Hubs and Spokes Structure.

3.2 Obtaining the New Boundary Location

As described in section 2, under the acted forces, the centerline deforms according to the dynamic law of the Mass-Spring system. It is presumed that only elasticity and curvature forces are applied on the centerline, while there is no constraint force. Therefore, the movements of the centerline are limited to translation and rotation around the atom or the combination of them, at the same time, there is no rotation around the central axis.

Above all, we propose the Orientation Vector mentioned in section 3.1. Orientation Vector, which is similar to the third element of Medial Representation, is used to establish the translation and rotation plane for the spoke. By translating the vector from the original point to the point after deformation, the centerline segment and the vector compose a plane, which contains the altered spoke.

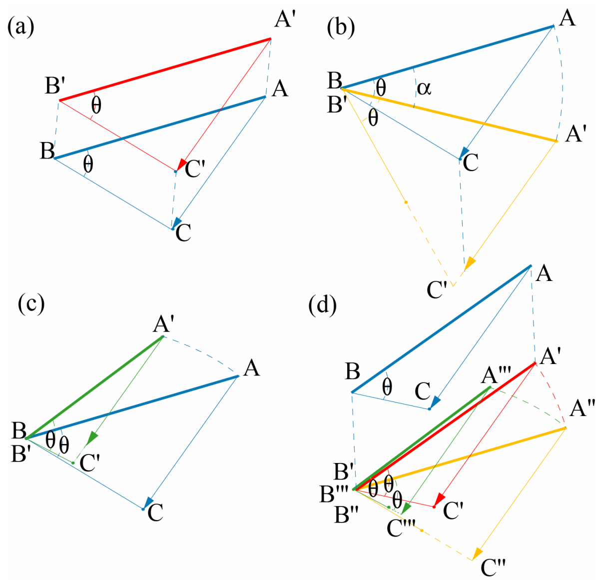

Fig. 5. (a) Translation. (b) Rotation within the Plane ABC. (c) Rotation vertical to the plane ABC. (d) Combination of Movements of (a), (b) and (c).

At this point, a lemma rule is introduced to validate the existence of the plane during dynamic deformation. Given the original atoms of *A*, *B*, the original boundary point *C*, and the deformed atoms of *A'*, *B'*, deformed boundary point *C'*, the lemma rule is described as the 4 cases below: 1) the centerline *AB* is translated to *A'B'* and the Orientation Vector *AC* is also translated to *A'C'* to determine the plane containing the moved spoke *B'C'*; 2) limited in the plane defined by centerline and spoke, rotating the centerline *AB* around the medial atom to *A'B'*(*A'B*), obviously, the plane is the same one; 3) limited in the vertical plane *ABA'* to the current plane *ABC*, the centerline *AB* rotates around the axis, which passes through *A* and *AB* is vertical to plane *ABA'*, to *A'B'*(*A'B*), then we translate the Orientation Vector *AC* from *A* to *A'* to determine the plane containing the spoke *B'C'*; 4) all the other movements can be defined as the 3 cases above – given *A'''B'''* as the destination, translating the centerline *AB* from *B* to *B'* as *A'B'*, then rotating *A'B'* in the plane *A'B'C'* around *B'* as *A''B''* until *A''B''* is at vertical intersection between plane *A'B'A''B''(A'A'' B'')* and *A''B''A'''B'''(A''A''' B''')*, and finally rotating *A''B''* in the plane *A''B''A'''B'''(A''A''' B''')* to *A'''B'''*. Fig. 5 shows the principles.

Under the lemma rule introduced above, the spoke BC as well as the boundary C can be uniquely determined after the deformation, and it is calculated by the following equation:

$$C = x + R_{V,\overline{AB}}(\theta, \overline{AB}) \cdot r_{\overline{BC}} / |\overline{AB}| \tag{2}$$

where x is the coordinate of medial atom B; $R_{V,\overline{AB}}(\theta,\overline{AB})$ is the operator to rotate $\overline{AB}$ by the angle of θ within the plane determined by V and $\overline{AB}$ (the procedure is described in the lemma). $r_{\overline{BC}}$ is the length of $\overline{BC}$ and $|\overline{AB}|$ is the length of $\overline{AB}$ [9]. To determine the positions of other spokes as well as the boundaries, we simply rotate the spoke $\overline{BC}$ around the centerline axis $\overline{AB}$ and reset its length according to other spokes.

4 Experiments

Dynamic global deformation of elastic objects was implemented using Deformable Centerline and Medial Representation Method with a triangular mesh. On a 2.80 GHz Pentium IV PC with 1.0GMb DDR2 memory, and a GeForce 6800 graphics card, a centerline of 19 elements and a triangular surface mesh of 325 elements need about 0.02-0.04 seconds per time step. Fig. 6 shows the experimental results.

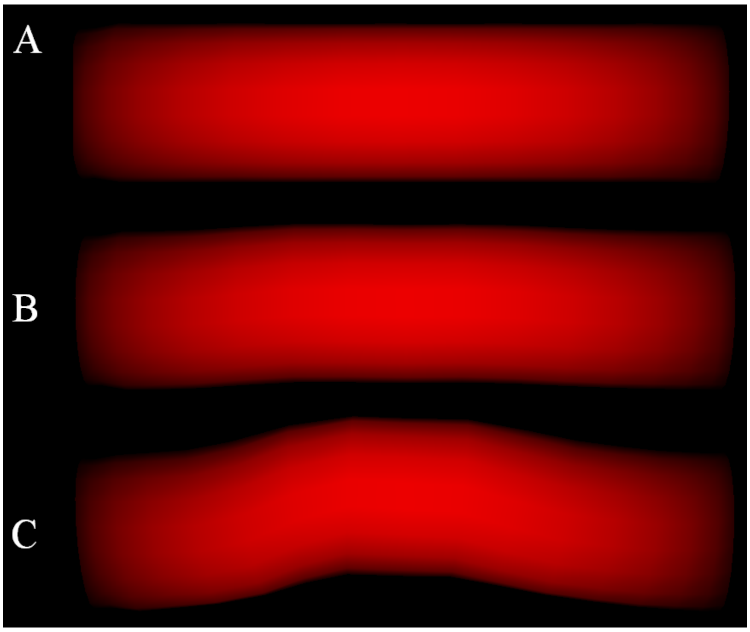

Fig. 6. (A) The Soft Tissue at Its Initial Status. (B) Bending Slightly. (C) Bending Intensively.

5 Conclusion

In this paper, a novel model is proposed to simulate the global deformation of soft tissue efficiently and effectively. This model combines the advantages of mass-spring model and medial representation model. On one hand, Mass-spring model is difficult to simulate large motion due to its inaccuracy of its linear mathematical formulation, but it is easy to solve. One the other hand, Medial representation method is ideal to represent the boundary information of an object however its computation cost is high.

As a whole, the proposed model uses deformable centerline of mass-spring system as the internal structure of soft tissue and applies simplified medial representation method to reconstructing and anchoring the boundary points.

In the future, we will endeavor to model more complicated soft tissue such as intestine, which has more rugae on the surface structure and a more roundabout and complex centerline structure, and some other organs which have long and narrow shapes. Aiming at a more accurate and robust level of virtual surgery, we will also exert ourselves to combine this model with the improved elastic model together and to refine the simulation.

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