Real-time Cutting and Suture Simulation Using Hybrid Elastic Model

Jingsi Zhang, Lixu Gu*, Pengfei Huang, Jalda Dworzak, Feng Chen, Xianming Kong*

***Abstract*—In this work, our aim is to model realistic cutting and suture in real-time. For realistic rendering, the response of deformable soft tissue during the cutting and suture process should be carefully analyzed and simulated. Therefore, different behaviors of tissue resistance need to be simulated in the different phases of tool-tissue interaction. In the first phase of cutting and suture, before the tool fractures the surface we model resistance of the tissue as surface tension. Afterwards, when the tool moves into the tissue, the friction between tool and soft tissue is simulated. In addition, a hybrid elastic model consisting of a mass-spring surface with a skeleton structure is employed to speed up calculation. In our research, an abstract blood vessel is used as a case study.**

Keywords: Virtual Surgery, Soft Tissue, Deformation, Cutting, Suture

I. INTRODUCTION

NOWADYS, virtual surgery is a promising application for the training of tomorrow's surgeons. Good surgical simulators enable surgeon trainees to perform different kinds of surgery gestures on a virtual organ. They provide for the familiarization with the response of soft tissue in a virtual training environment like in real surgery. Therefore, reasonable deformation as well as accurate force feedback is important for the development of a realistic surgery simulator.

The subject of this paper is lifelike simulation of cutting and suture, two fundamental surgical operations, in real-time. We analyze and model the response of soft tissue and forces during different phases of cutting and suture. In addition, a full-fledged surgical simulator needs to operate at an interactive rate. Thus, computational efficiency is another important requirement. In our study, we use a hybrid model to speed up calculations.

The paper is organized as follows: Section 2 introduces the related work on cutting and suture simulation. Section 3 describes the hybrid elastic model. In Section 4 and 5, approaches to simulate cutting and suture are discussed in detail. Finally, in Section 6, experiments are presented.

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II. RELATED WORK

Most of the reported work on cutting simulation mainly focuses on how to form a cut by modifying the mesh topology. In [1], edges are removed where the scalpel encounters the mesh. More recently, new methods have been proposed. Subdividing triangles or tetrahedrons [2], [3] is introduced in order to keep the area or volume invariant. A proposed snapping method [4] maintains the number of mesh elements and reduces calculation time. However, few of them mentioned tissue deformation during the cutting process. In this paper, we use the snapping method to modify the mesh topology during the cutting process. At the same time, the soft tissue deformation during cutting is characterized by an extension of snapping method with force simulation during tool-tissue interaction.

Prior work towards suture simulation proposed several suture models. Suture models have been simulated by mass springs [5], [6]. It is easy to model force along the suture, but the method is unstable especially when the lengths of suture segments become non-uniform. Moreover, elastic models do not work like real suture. Brown et al. model the suture as rigid links. They use "constraint points" and the "FTL" algorithm to configure the motion of the suture [7]-[9]. The method is easy to implement and fast in computation. However, it is imperfect in that there is no force model in the suture. Without force model, this method is inapplicable for haptic rendering. Moreover, suture is moved geometrically instead of physically lacks realism in visual rendering. Lenior et al. [10] models suture as splines, but it does not yield reasonable deformation. In our suture simulation, we modify the method of [7]. We use force to move the suture and the soft tissue during the suture-tissue-interaction. This results in a realistic and physically reasonable suture simulation.

III. MASS SPRING MODEL WITH SKELETON STRUCTURE

The mass-spring model is a popular method of deformable modeling. It discretizes the simulated body into a set of masses that are interconnected by springs and dampers. It employs a differential equation to compute the coordinates of mass points [9]:

$$m_i \frac{\partial^2 x_i}{\partial t} + d_i \frac{\partial x_i}{\partial t} + \sum_{j \in \sigma(i)} k(i,j) \cdot \delta l(i,j) = F_i \quad (1)$$

m_i, d_i and F_i represent the mass, damping factor and the outer force appended on the i th mass point. $k(i,j)$ and $\delta l(i,j)$ indicate the elasticity factor and the displacement of spring ij respectively.

To speed up calculation, we introduce a hybrid model, which consists of a mass-spring surface and a mass-spring centerline. Each surface point is connected with its nearest centerline point. A dynamic surface-reconstruction mechanism is employed to reconstruct the surface once the centerline is deformed [11], [12].

We localize deformations on the surface. The use of localization restriction on the surface model greatly reduces the computational effort, but it causes unrealistic deformation. Therefore, we introduce the centerline that induces global deformation. Once a force is applied to the surface, its propagation onto the surface is restricted to the neighboring area. Meanwhile, the force is also transferred to the centerline. The surface area connected to the deformed part of the centerline will deform globally. Fig.1.A shows a blood vessel using the hybrid model. Fig.1.B illustrates a surface model with localization restriction. The green plate applies a downward force to the model. The lighter area on the surface indicates the localization region. The figure shows that the hybrid model is more realistic. Thus, the hybrid model provides a good balance between efficiency and realistic rendering.

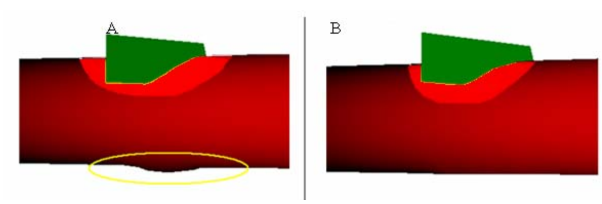

Fig.1. Comparison of two models: A. hybrid model and B. Surface

IV. Cutting Simulation Approach

A. General cutting process

Consider general scalpel cutting. In the early phase of cutting, the surface tension will resist the force from the blade. The surface will be stretched up to a certain threshold (Fig.2.(a)). Once the surface exceeds that threshold, referred to as the maximal skin tension, the surface will fracture (Fig.2.(b)). Meanwhile, the surface tension is released and a slight recoil of the surface emerges (Fig.2.(b)). Afterwards, while the blade continues cutting into the soft tissue, friction is applied between the tissue and the blade as long as they are interacting (Fig.2.(c)).

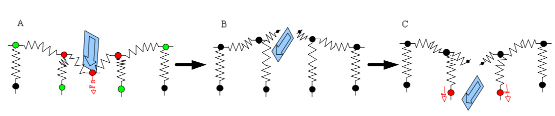

Fig.2. General cutting process: A. Surface tension, B. Fracture, and C. Friction simulation.

In the future, the value of maximal surface tension and friction could be obtained from experiments on real soft tissue. In this paper, we predefine them as K and F, which can yield realistic simulation.

B. Extended snapping method to model soft tissue deformation during cutting

Snapping is a popular approach to model cutting. It models incision smoothly without changing the number of triangles on the surface mesh. The way it modifies the mesh topology is shown in Fig.3.

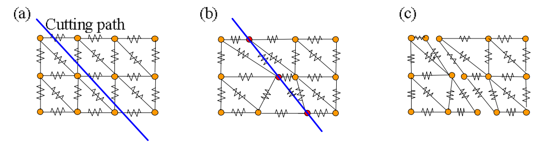

Fig.3 Traditional snapping method: (a) The original mesh, (b) Snapping, and (c) Incision modeling

We slightly adjust traditional snapping for the simulation of surface tension and friction. Fig.4 shows how surface tension is simulated in combination with snapping. We add a phase between snapping and incision modeling (Fig.4.(c)). When the blade stretches the surface, we compute surface tension by summing up the internal force of the soft tissue, compare it with the threshold, and decide whether the surface will fracture. When the surface cracks, the incision is modeled immediately.

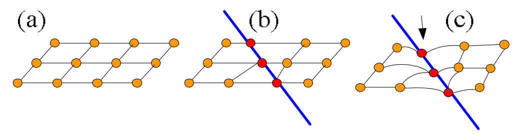

Fig.4. Extend snapping method to simulate surface tension :(a) Original mesh, (b) Snapping, and (c) Surface tension simulation

To simulate friction, we apply a pair of equal and opposite forces on the collided part of soft tissue and the blade once they have relative motion.

Since the soft-tissue-model's force and the tool's force is exactly a pair of action-reaction forces, we obtain the tool's force by calculating the composite of internal force of the soft tissue model.

V. Suture Simulation Approach

Due to the character of soft tissue, the tissue response varies in the different stages of the suture operation.

At first, when the needle pushes onto the surface, the tissue resists the surface penetration of the needle. Here, the surface tension serves as resistance. Afterwards, when the surface tension reaches a limit, the needle will penetrate the surface and the suture will slide into tissue. Friction will prevent the sliding. Finally, the suture pulls the two ends of the object together. The suture tension serves as pulling force. In the following sections, the method that simulates the behaviors stated above is discussed and an algorithm to compute suture tension in real-time is outlined.

A. Suture model

It is more realistic to model suture as a rigid object, because suture is non-elastic. Similar to [7], we also model suture as a series of rigid links and use "constraint nodes" to configure the motion of the whole suture in each cycle. "Constraints" are caused by tissue-suture collision or suture's attachment with the needle. In Fig.5, we can see the two kinds of constraints. Non-constraint points are moved towards their adjacent constraint point. Once the constraint points' positions are known, Non-constraint points' positions are specified by FTL method [7].

Unlike [7], we simulate forces on the suture. Constraint nodes' motions are determined by forces applied on them. Constraint points divide the suture into several suture segments. A method to compute suture tension of each suture segment in real-time will be introduced later. We compute outer force on each constraint point and obtain their velocity and position accordingly. For the constraint node at tissue-suture intersection, its mass is the sum of intersected suture node and tissue node, and its outer force is the composite of suture tension from the suture node and spring forces from tissue node.

For the constraint point connected to the needle, its position should agree with the needle. The force feedback to the user corresponds to the tension of the first suture segment.

B. *Piercing operation and frictional sliding simulation*

The piercing operation is simulated as illustrated in Fig.5(a.1) and Fig.5(a.2). The surface tension resists the penetration of the needle at first. Once it exceeds the threshold, the needle will pierce through the surface.

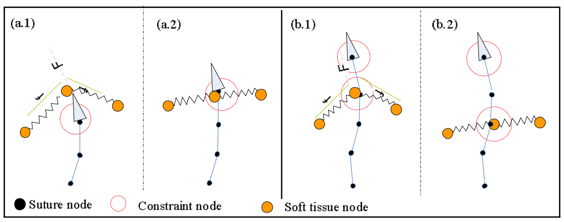

Fig.5 (a.1) First stage of the piercing operation (a.2) Piercing through the surface. (b.1) Friction prevents relative motion (b.2) Suture slides

Frictional sliding is simulated as shown in (Fig.5(b.1)) and (Fig.5(b.2)). The friction prevents sliding of the suture at first. The moment the friction exceeds a threshold, the suture slides. At the same time, the condition of the constraint node is transferred to the adjacent suture node that is pulled into the position of the penetrated soft tissue node.

C. *Suture tension computation*

In our method, we handle the tension value of each tensile suture segment as variables and the force on adjacent tissue node as conditions. We assume that every constraint node is at a force-balanced status. From this, we obtain a set of equations. Solving these equations, we can get an approximated tension value of each tensile suture segment. The method is shown in ALGORITHM 1. If the user pulls the suture, a slight increase of the force is added to the tensile segments. This results in the movement of the suture.

ALGORITHM 1
SUTURE TENSION COMPUTATION METHOD

Algorithm: Suture force computation

1. $N_0, N_1, \ldots, N_k$ are constraint nodes of the suture.
2. Get conditions:
For each constraint node at tissue-suture intersection ($N_1, \ldots, N_k$), compute the composite of spring forces from the tissue node, note them as $F_1, F_2, \ldots F_k$.
3. Get variables:
For every constrain node i (i = 0,1,…,n-1)
    If N_iN_{i+1} is a tensile suture segment
        Then note its tension value as $X_{i,i+1}$
    Else
        Let $X_{i,i+1} = 0$
4. Get equation set:
For every each node i (i = 1,…,n) at tissue-suture intersection, add a equation to the equation set:
$$X_{i-1,i} + F_i + X_{i,i+1} = 0$$
5. Get result:
Compute the result of the set of equations and get the value of each X

Our method requires little computation time and yields haptically realistic result. However, it needs to be refined for more accuracy in our future work.

VI. EXPERIMENTS

All result presented in this section were measured on a standard PC that is equipped with:

1) Intel Pentium M 1.7G Hz CPU
2) 1GB Bytes of DDR2 Memory
3) GeForce 6800 Graphics card

A. *Hybrid model evaluation*

The model is an artificial blood vessel, which consists of 1142 mass points and 2280 surface triangles.

Comparison of the calculation time necessary for one simulation time step between different models is shown in TABLE1. This table indicates that hybrid model is faster than the pure surface model but a bit slower than the surface model with localization restriction. However, regarding visual rendering quality, the hybrid model is a good choice.

TABLE 1
COMPUTATION TIME OF DIFFERENT MODEL (MILLISECONDS PER UPDATE TIME)

	Surface model	LR Surface model	Hybrid model
LF(20)	1.280	1.168	1.264
LF(50)	1.476	1.346	1.375
GF(100)	2.371	1.289	1.782
GF(500)	2.562	1.617	1.938

LR surface model = surface model with localization restriction; LF = local force (a relatively small force appended in one mass point on the model); GF = global force (a large force applied on 10 random points on the model); 20, 50, 100, 500 = the magnitude of the force

B. *Cutting with force simulation*

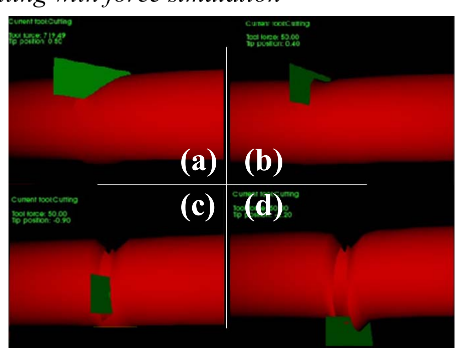

Fig.6.a typical cutting process: (a) Surface tension simulation, (b) Surface fractures, (c) Friction simulation and (d) Complete cutting

Fig.6 shows the appearance of a typical cutting process on a virtual blood vessel. Fig.6(a) depicts the simulation of surface tension, where (b) shows the moment when the surface tension exceeds the threshold. The surface tension is immediately released and the surface fractures. Fig.6(c) illustrates the friction simulation. In Fig.6(d) the cutting procedure is completed.

Force is calculated every time step. Fig.7 shows the feedback in a typical cutting process.

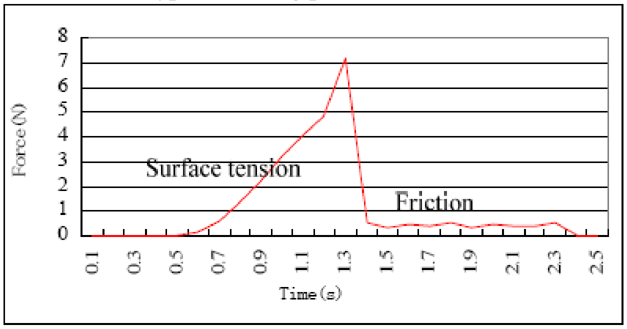

Fig.7. measured force during a typical cutting process

C. *Suture simulation with force measurement*

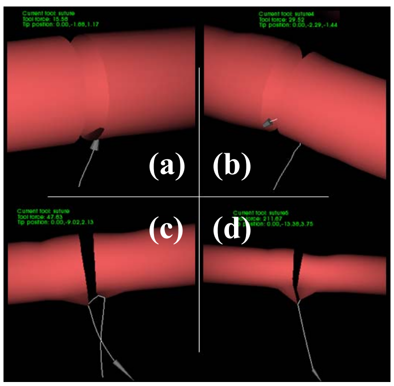

Fig.8. A typical suture process. (a): Piercing one end of the blood vessel. (b): Sliding and piercing another end. (c) sliding. (d) Pulling the two ends together

Fig.8 shows the execution of a typical suture process on a virtual blood vessel. We assume that there is a knot at one end of the suture, which cannot slide through the soft tissue. Therefore, in case we continually draw the needle, the suture will finally pull the two ends of the model together.

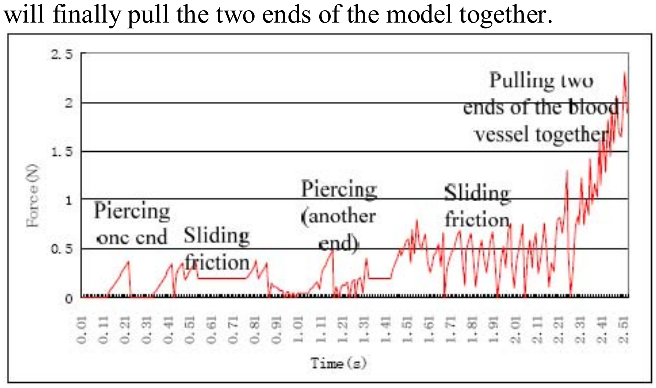

Fig.9 measured force during a typical suture process

Fig.9 shows the force measurement in a typical suture process. The first peak appears when the needle pierces one end of the blood vessel. Then sliding friction follows when the suture slides through the tissue. The next peak appears when the needle pierces the other end. At last, the force continually increases when the two ends of the model are pulled together.

VII. CONCLUSION AND FUTURE WORK

In this paper, we present a realistic and real-time soft tissue cutting and suture simulation. Response of soft tissue is simulated realistically while forces are properly modeled throughout the whole cutting and suture process. However, there are some drawbacks in our work. The hybrid model is computationally fast but unsuitable to model complex organs. The method to compute suture tension operates efficiently at the expense of accuracy. Knot tying is not included in suture simulation. In the future, to achieve efficiency as well as accuracy, modeling methods and suture-tension computation methods should be refined, and knot-tying work needs to be added to form a complete suture simulator.

REFERENCES

[1]. S. F. Frisken-Gibson, “Using linked volumes to model Object collisions, deformation, cutting, carving and joining”, IEEE transaction on visualization and computer graphics, VOL.5, No.4, 1999.

[2]. D. Bielser, and M. H. Gross, “Interactive simulation of surgical cuts”, Proceeding of Pacific Graphics, 2000.

[3]. A. B. Mor and T. Kanade, “Modifying Soft Tissue Models: Progressive Cutting with Minimal New Element Creation”, Medical Image Computing and Computer-Assisted Intervention MICCAI, Volume 1935, October 2000

[4]. H. Nienhuys and A.F.V.D. Stappen, “A surgery Simulation Supporting Cuts and Finite Element Deformation”, Medical Image Computing and Computer-Assisted Intervention, MICCAI LNCS 2208, pp 145 – 152, 2001

[5]. M. LeDuc, S. Payandeh, and J Dill, “Toward modeling of a suturing task”, Graphics Interface, 2003.

[6]. P.Marshall, S. Payandeh, J. Dill, “A study on haptic rendering in a simulated surgical training environment”, Symposium on haptic interface for virtual environment and teleoperator system, 2006

[7]. J. Brown, K. Montgomery, J. Latombe, and M. Stephanides, “A Microsurgery Simulation System”, Medical Image Computing and Computer-Assisted Intervention MICCAI, LNCS 2208 pp. 137-144, 2001

[8]. J. Brown, J. C. Latombe, and K Montgomery, “Real-time knot-tying simulation”, The Visual Computer pp.165–179, 2004

[9]. J. Brown, K. Montgomery, C. Bruyns, J. Latombe, K. Montgomery, and M Stephanides, “Real-time simulation of deformable objects: tools and application”, The fourteenth conference of Computer animation. Proceedings, pp. 228-258, 2001

[10]. J. Lenior, P. Meseuer, L. Grisoni, and C. Chaillou, “A suture model for surgical simulation”, 2nd International Symposium on Medical Simulation ISMS pp.105-113, 2004

[11]. H. Pengfei, G. Lixu, and Z. Shaoting, “Real-Time Simulation for Global Deformation of Soft-Tissue Using Deformable Centerline and Medial Representation”, International Symposium on Computational Models for Biomedical simulation, ISBMS, pp67-74, 2006

[12]. S. Zhang, L. Gu, W. Liang, J. Zhang, and F. Qian, “Real-Time Virtual Surgery Simulation Employing MM-Model and Adaptive Spatial Hashing”, International Conference on Artificial reality and Telexistence, ICAT, 2006