SIMULATION OF SURGICAL CUTTING USING A PROGRESSIVE CUTTING SCHEME AND EXTENDED FINITE ELEMENT METHOD

Yi Ding[1], Stephane Bordas[2], Paul Rosin[1], David Marshall[1]

Cardiff University, CF24 3AA[1]
University of Luxembourg, L-1359[2]

Abstract
Accuracy and speed are two of the most important problems in the real-time Finite Element Method (FEM)-based simulations of surgical cutting [1][2]. While the latter can be gradually eased through GPU-based acceleration[3][4], the former hasn't been properly addressed even until recently. To enable realistic and accurate simulation, the cutting line should follow the exact movement of the user-controlled virtual scalpel in real-time. However problems in the collision detection and the cutting scheme can easily result a wrong response such as 1) Elements have been cutted before virtual scalpel's arrival, 2) an obvious lag between the virtual scalpel and the model modification. A progressive cutting scheme was proposed in recent years to minimise the lag problem[5]. But it is based on the mesh subdivision in a standard FEM approach. Extended Finite Element Method (XFEM) which has the advantage of modeling arbitrary cuts without modifying the underlying mesh is favoured in this work over the standard FEM [6][7][8]. This work seeks to improve the simulation of surgical cutting by combining both a progressive scheme and xFEM. Experiments based on the (Simulation Open Framework Architecture) have successfully demonstrated the surgical cutting simulation with the proposed idea.

KEY WORDS: SURGICAL CUTTING SIMULATION, PROGRESSIVE CUTTING, EXTENDED FINITE ELEMENT METHOD (XFEM)

1 Introduction

Cutting is one of the most important skills in surgery. With the increasingly-popular surgeries such as Minimal Invasive Surgeries (MIS) such as laparascopic surgeries, the cutting skills are also more demanding. So excessive training is required before surgeons can perform this kind of surgeries. Conventional trainings are done using 1) human anatomical models with the guidance of surgical consultants, 2) real patients 3) dead bodies. But they suffer from a number of drawbacks respectively. For 1), it is very costly and labouring because of consultant's involvement, For 2) it places patients' lives at risk, For 3), it doesn't have the dynamic responses as living bodies, so the potential learning outcome is reduced. In general, all the three approaches don't allow objective and quantitative assessment of the surgical skills

On the other hand, computer simulation of surgical cutting provides a cost-effective and objective-assessing approach to train medical professionals before they can perform these kinds of demanding surgeries. Studies on the skill training of other industries such as flight pilot training have proved that computer simulation-based training can drastically reduce training time and cost, and significantly improve the overall training outcome. Different to many previous simulators based purely on computer graphics, the computer system has two key features, firstly, it provides users with a virtual environment that also includes haptic feedback, i.e. the sense of touch including vibrations, forces and motions between the surgical instrument and patient's tissues, a kind of information very important to MIS. Secondly, by fusing the knowledge from biomechanics and haptics with computer graphics, the dyanmic organ responses are supported by real mechanical behaviours and the haptic forces are directly related to the real-time mechanical responses of human organs, rather than artificially generating the virtual responses as those based on computer graphics.

Finite Element Method is commonly used in biomechanics for generating the dynamic tissue responses. Accuracy and speed are two of the most important problems in the real-time FEM-based simulations of surgical cutting. While the latter can be gradually eased through GPU-based acceleration[3][4], the former hasn't been properly solved even until recently. One main problem is the obvious lag between a scalpel's movements and the cutting response. To enable realistic and accurate simulation, the cutting response should follow the exact movement of the user-controlled virtual scalpel in real-time. In this work, we propose a new cutting approach based on a progressive cutting scheme and eXtended Finite Element Method (XFEM) to improve the accuracy. The reason XFEM is used is because it is capable of modelling arbitrary cuts without affecting the mesh quality as compared to the standard FEM. Successful experiments have been demonstrated on the (Simulation Open Framework Architecture) Sofa package.

2. Biomechanics

Human body organ biomechanics are complex, two types of complexities should be considered 1) Heterogeneous material**,** 2) Nonlinear deformations. It has been shown that the combination of linear elasticity and FEM is able to model the behaviours for simple soft tissues [1]. This can be interpreted as, locally, each tissue element obey mass-spring model. Globally, FEM is used to generate the deformation response. The utilisation of FEM will address the two mentioned problems above, it is capable of solving the nonlinear system of equations which consisting of different heterogeneous tissue types.

2.1 Static tissue response

Originally, FEM is used in solving a static equation below

$$\mathbf{K}\cdot\mathbf{u} = \mathbf{f} \qquad 1)$$

Here **K** is the stiffness of the soft tissue, **u** is the displacement of the soft tissue and **f** is the force. Basically, we want to predict the deformation response u by applying a force through a virtual tool. Based on the equilibrium theory of thermal physics, the outside energy (applied by the force) is equal to the internal energy encompassed by the product of element stiffness matrix and the element displacement. So the classical FEM solution is to find the corresponding displacement which minimises the total deformation energy.

2.2 Dynamic tissue response

To dynamically interact with a FEM-based system, a motion function denoted by M-B-K is used [2]

$$\mathbf{M}\cdot\mathbf{u''} + \mathbf{B}\cdot\mathbf{u'} + \mathbf{K}\cdot\mathbf{u} = \mathbf{f} \qquad 2)$$

Here u'' is the acceleration, u' is the speed and u is the displacement. M is the body mass, B is the damping factor, K is the stiffness matrix as before. So instead of solving a static ku = f as mentioned in 1), we try to solve this motion function to generate the dynamic response. This can be done very efficiently for real -time simulations through an iterative scheme. Here we use two different discretisation methods for discretising a soft-tissue region: finite difference in time and finite element in space.

3. Simulation of surgical cutting

3.1) Extended Finite Element Method

The Here we use xFEM to evaluate the element stiffness of the discontinuous regions caused by the cut.The main idea of xFEM is to construct basis shape functions through products of classical shape functions and a local enriched one which allows the generation of discontinuous elements. So, the equation of the displacements can be generally formulated as

$$u(x) = \underbrace{\sum_{i\in I} N_i(x)u_i}_{classical} + \underbrace{\sum_{j\in J} N_j(x)\psi_j(x)a_j}_{enrichment} \qquad 3)$$

where N_i (x) are the classical shape functions; the discontinuous enrichment functions are denoted by ψ_j (x), and the new nodal DOFs as a_j. I is the standard finite element domain, J is the xFEM enrichment domain. The enrichment function ψ(x) can be any discontinuous function; For example, it can be is a Heaviside function in standard form or in shifted form. In standard- form, it is written as

$$\psi(x) = H(x) = \begin{cases} +1 & \text{one side of the cut} \\ -1 & \text{the other side of the cut} \end{cases} \qquad 4)$$

In shifted-form, it is written as

$$\psi_i(x) = \frac{1}{2}(H(x) - H_i) \qquad 5)$$

where H_i is the value of Heaviside function at the i-th node. The shifted-form function consists in using the enrichment contribution only inside of the discontinuous element and ignores the contribution on the borders and outside of the element. It ensures the delta property by computing the displacement of the enriched nodes as the sum of the components $u_i + \psi_i a_i$. The shifted function in contrast with the standard Heaviside, uses both u_i and the added DOFs a_i for an enriched element.

At the tip of the cut, obviously it is much stiffer than the rest along the cut. The above xFEM formation is not longer suitable for evaluating the stiffness at the cut tip. So a new enrichment function is used which considers the radial and angular behaviour of the asymptotic linear-elastic cut-tip displacement. It is given by

$$\{F_l(r,\theta)\}_{l=1}^{4} = \left\{\sqrt{r}\sin\frac{\theta}{2}, \sqrt{r}\cos\frac{\theta}{2}, \sqrt{r}\sin\frac{\theta}{2}\sin\theta, \sqrt{r}\cos\frac{\theta}{2}\sin\theta\right\} \quad 6)$$

where r and θ are the local polar coordinates of a point's position measured against the crack tip location.

Finally, the enrichment function can be states as

$$u(x) = \underbrace{\sum_{i\in I} N_i(x)u_i}_{\text{classical}} \underbrace{\sum_{j\in J} N_j(x)\psi_j(x)a_j}_{\text{standard enrichment}} + \underbrace{\sum_{k\in K} N_k(x)\left(\sum_{l=1}^{4} F_l(x)a_k\right)}_{\text{tip enrichment}} \quad 7)$$

where I, J, K refer to classic FEM enrichment domain, standard enrichment domain (i.e. excluding cut tip) and the cut tip enrichment, a_k is the new DOFs brought by the tip enrichment.

3.2) A progressive scheme

A progressive cutting scheme was proposed in recent years to minimise the lag problem [5]. But it is based on the mesh subdivision in a standard FEM approach. As shown in Figure 1, a scalpel's movement inside an element is tracked where it moves. So this scheme is able to model the exact movements of a scalpel inside each element under cutting as it progresses, in contract to conventional one which can model its movement at element edges, i.e. when it completed the cut of an element.

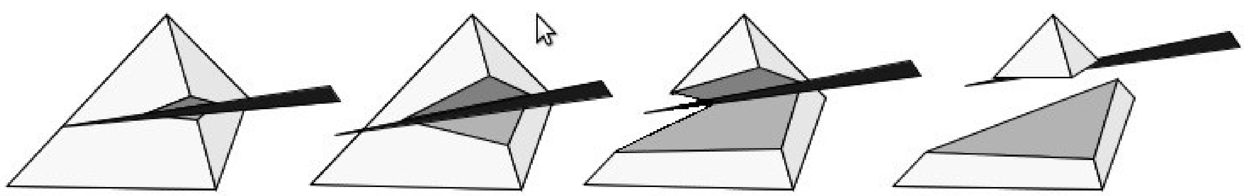

Figure 1 The progressive cut – Scalpel's movement inside each element is tracked.

The progressive scheme with regarding the evaluation of element stiffness can be best explained in a 2D example below.

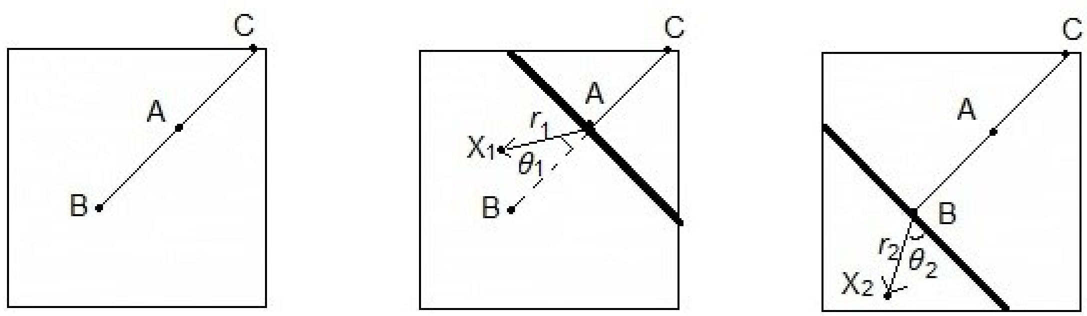

Figure 2 Evaluation of the element stiffness in the progressive cutting: Suppose we have started a cutting from point C. (a) Now we want to make a cut from point A to point B. (b) The stiffness evaluation at point A, (c) The stiffness evaluation at point B. (r_1,θ_1) (r_2,θ_2) are radial and angular values with respect to a point X_1 and a point X_2 for the stiffness evaluation at the cut tip A and B respectively. The bold lines for both the centre and right figures divide the stiffness evaluation regions into 2 parts.

In Figure 2, we have already made cut inside an element from point C. Now want to make a cut from point A to point B. In the conventional cutting, a cut response is made only when a new element edges have been broken. Here from A to B, no new edge is broken, so the conventional cutting wouldn't be able to generate any cutting response. Being a progressive scheme, it is aimed at solve this problem by evaluating the different element stiffness with regard to A and B, and then generate the corresponding visualisation effects to show the new discontinuous region from A to B. For the situation in Figure 2b, the stiffness is evaluated as the summation of the standard enrichment for segment A to C and the cut tip enrichment at A. For the situation in Figure 2c, the stiffness is evaluated as the summation of the standard enrichment for segment B to C and the cut tip enrichment at B. Obviously they are quite different. So using the above method we will be able to evaluate the corresponding element stiffness in this progressive cutting scheme.

3.4) Visualisation

The benefits of xFEM is it has added new Degrees Of Freedom (DOFs) to the original FEM mesh, so enabling more flexible and accurate evaluation of element stiffness without messing up mesh quality. However, these added DOFs which have different physical properties cannot be visualised based on the original FEM whose DOFs are fixed and limited. Therefore, it is better to treat the visualisation of the cutting separately from the evaluation of element stiffness. To visualise the cutting progressively, we track the position of the cutting inside the mesh and then adjust the mesh's internal structures correspondingly. Several schemes have been proposed such as [7] which creates new discontinuous element to replace the original continuous mesh, and [5] which subdivide the mesh into smaller elements and use the element boundaries to visual the cut. The problem with the latter is that it is based on a standard FEM approach, so the many very small elements (very dense matrices) created by this mesh subdivision scheme is likely to cause problems to evaluation of the element stiffness.

On the other hand, this would not be a problem to our proposed scheme because although we adopt the mesh subdivision scheme to visualise the cutting progressively, the element stiffness is evaluated in the original mesh structure in the xFEM framework.

4. Experiment

4.1. Simulation Open Framework Architecture (Sofa)

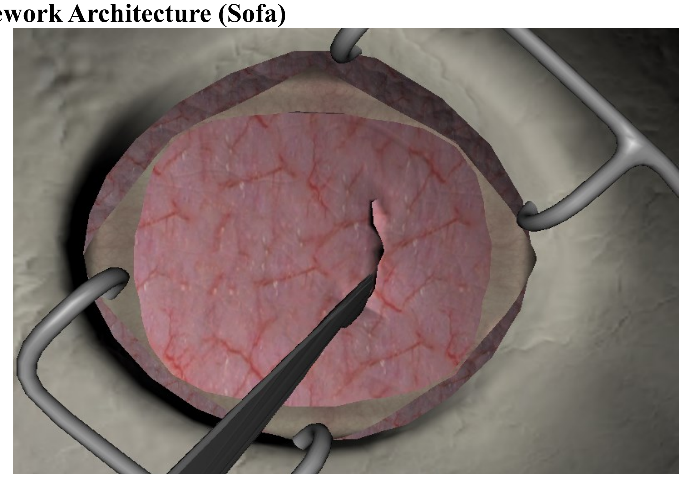

Figure 3 Demonstration of successful simulations of surgical cutting using xFEM and the progressive scheme in Sofa

Sofa s an Open Source framework primarily targeted at real- time medical simulation, with an emphasis on medical simulation. It is mostly intended for the research community to help develop newer algorithms, but can also be used as an efficient prototyping tool or as a biomechanics or physics engine. It consists of a deformation (biomechanic) model, a collision model (computer graphics) and visual model. Consistency is done through mapping.

Figure 3 shows that cutting is performed for a brain surgery. The strain and stresses of each element along the cutting are updated as it progresses. The deformation of the cutting interface are computed from the proposed xFEM method. Based on feebacks from surgical consults, the simulation is able to emulate the soft-tissue deformation and cutting response as is done for the real surgical cutting. Due to time restraint, the proposed approach is only evaluated visually and not quantitatively. Regarding the "lag" problem between the cutting response and the scalpel' movement, the proposed approach is able to generate the cutting response wherever it moves. However, this is computationally demanding and costly for evaluating the element stiffness matrices using the xFEM method. To solve this problem, we only evaluate the stiffness at certain sample points, so called "keyframe" within each element along the cutting path, and the rest will be computed using bilnear interpolation. Using this method, we can achieve good speed and maintain reasonably-high accuracy.

5. Conclusion

In this work, we proposed a new method for the simulation of surgical cutting. It is based on xFEM with a progressive cutting scheme. The idea of this progressive scheme is to alleviate the time lag problem in the cutting response from a scalpel's movement. The progressive scheme works by tracking the position of the scalpel's movement, then evaluating the corresponding element stiffness in real-time. On a separate pipeline, it is coordinated with the visual remeshing algorithm which adjusts the mesh's internal structures to display the discontinuous cut accordingly. Experiments using Sofa has demonstrated successful real-time simulation of cutting with minimised lag problem. In the future, it is more reasonable to evaluate the accuracy of the cutting, such as compared it with the cutting of a real soft-tissue captured by a 3D motion-based vision system. Based on the initial visual assessment by the surgeons, the simulation resembles the real cutting quite well.

References

[1] C. Duriez, F. Dubois, A. Kheddar, C. Andriot, 2006. Realistic hapic rendering of interacting deformable objects in in virtual environments, IEEE Transactions on Visualization and Computer Graphics, Vol. 12, No. 1, pp. 36-47, 2006.

[2] M. Nesme, Y. Payan, F. Faure, Efficient, physically plausible finite elements, EUROGRAPHICS'05, pp.1-4, 2005.

[3] H. Courtecuisse, H. Junga, J. Allard, C. Duriez, D. Lee, S. Cotin, GPU-based real-time soft-tissue deformation with cutting and haptic feedback, Progress in biophysics and molecular biology, Vol. 103, No. 2-3. pp. 159-68, 2010.

[4] H. Courtecuisse, P. Kerfriden, C. Duriez, J. Allard, S. P. A. Bordas, S. Cotin, Real-time simulation of surgical cutting in biological tissues using a semi-implicit time integration scheme, International Conference on Computational Mechanics, 2013.

[5] A. Mor, T. Kanade, Mofifying sof tissue models: Progressive cutting with minimal new element creation. International conference on Medical Image Computing and Computer Assisted Intervention. pp. 598-707, 2000.

[6] First A. Author, Second B. Author and Third C. Coauthor. [6] T. Belytschko, T. Black, Elastic crack growth in finite elements with minimal remeshing. International Journal of Numerical Methods in Engineering, Vol. 45, No. 5, pp. 601-620, 1999.

[7] L. Gutierrez, F. Ramos, XFEM framework for cutting soft tissue – including topological changes in a surgical simulation, International conference on Computer Graphics Theory and applications, pp. 275-283, 2010.

[8] L. Vigneron, S. Warfield, P. Robe, J. Verly, 3D xFEM-based modeling of retraction of preoperative image update, Computer Aided Surgery, Vol. 16, No. 3, pp. 121-34, 2011.

[9] J. Allard, S. Cotin, F. Faure, P. Bensoussan, F. Poyer, C. Duriez, H. Dellingette, L. Gisoni, SOFA – an open source frmework for medical simulation. Medicine Meets Virtual Reality'07. pp. 1-6, 2007.