Haptic Rendering of Drilling Process in Orthopedic Surgical Simulation Based on the Volumetric Object

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***Abstract*—Drilling process is a basic skill used in almost all kinds of orthopedic surgeries. Currently, the virtual reality based surgical simulator is still lacking the realism and fidelity to convincingly challenge the actual operation experience on patient. In this paper, to obtain the balance between the high refresh rate of the haptic computation and the well visual result of the virtual environment, we employ a composite data structure to represent the three dimensional bone model. Furthermore, we make some improvements on the traditional voxmap point shell collision detection algorithm to be adapted to the contact model with frequent topology changes. Finally, a force computation method that can handle inhomogeneous bone material is developed based on the mechanical model. With this method, key features of the force sensation changing in the drilling process could be represented in a smooth way.**

***Index Terms*—Drilling simulation; Collision detection; Feedback force computation; Surgical simulation.**

I. Introduction

Drilling process is a basic skill used in almost all kinds of orthopaedic surgeries. The instruments that perform the drilling might have different kinds of configuration or size, but all the purpose is to set up a hole and put a screw in it. In several cases, if the performance is inappropriate, the drilling will cause complex complications or serious outcomes. For example, in the surgery to repair the bone fracture, surgeon needs to drill a few holes and uses a screw to fix the fractured bone pieces. Since the bone in the fracture region is already very fragile, drilling under this circumstance should be very careful and the drilling path shall be keeping along the axis to avoid a second fracture injury. In the other surgery such as the pedicle screw insertion, the area to perform the drilling has a lot of vital nerves and vessels. A very minor deviation may lead to unpredictable medical accident and bring a huge pain to the patient. Therefore, orthopedic surgeon needs to keep practicing in order to make each drilling procedure accurate enough.

Training this basic skill of the bone drilling is a problem for the medical school or hospital all the time. The shortage of the training opportunities is especially critical. Although virtual reality based training offers a cost-effective, safe and repeatable alternative to the traditional methods, the realism and fidelity of the system are still insufficient compared to the actual surgical scene. In the drilling process, the surgeon cannot observe the inside while the instrument penetrates into the depth of the bone. Therefore, a very important judgement criterion of the location and status of the drill is the sensation on hand. Surgeon can know whether the drill has already passed the cortical bone and reached the cancellous part, or whether the drill has been over cut and already punched through the bone. To create a realistic training simulator, a high-fidelity haptic rendering algorithm for the drilling is required to convey all the force features encountered in the process to the surgeon.

In order to distinguish the bone regions with different materials, the volumetric data structure of the three dimensional bone model is generally adopted. In the previous work, several researchers have developed the haptic rendering methods for bone drilling based on this type of data. Acosta et al. [1] presented a collaborative virtual reality based simulator to facilitate the team-oriented training of the drilling process. The interactive force on the drill was computed with a collision force and a local force gradient. Due to the workload of frequent volumetric updates, this system employed a client-server architecture to carry out the haptic computation and the visual computation in different terminals. A hybrid data structure was generated in the visuohaptic simulation by Morris et al. [2] to leverage the high haptic refresh rate and the acceptable visual effect. The haptic model in this work is computed by adding all the voxel normals contacting the instrument. In [3], Agus et al. applied the elasticity theorem to solve the contact forces between the burr and the bone material. Arbabtafti et al. [4] gave a physics-based training simulator and the machining theorem on metal was used to obtain the burring force at contacts. There are also some other work focusing on this topic, such as [6], [7]. However, the multiple material properties of the bone are not discussed in these works.

In this paper, we develop a surgical simulation for the bone drilling process. To obtain the balance between the high refresh rate of the haptic computation and the realistic visual result of the virtual environment, we employ a composite data structure to represent the three dimensional bone model. This data structure allows us to set different material properties

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according to the bone's structure. A fast conversion method that converts the volumetric data to the triangular mesh is also provided. Moreover, we improve the traditional collision detection algorithm for the volumetric data. Through additionally checking the internal points and the points in the moving paths of the shell points, the area swept by the instrument can be completely targeted and removed during the drilling process so that there will be no contact leaking in the collision detection. Finally, a force computation method is designed to handle the inhomogeneous property of the bone material based on the mechanical model. With this model, key features of the force sensation changing in the drilling process could be represented in a smooth way.

This paper is organized as follows. Section 2 describes the composite data structure for scene modeling. Section 3 details the simulation principle of the drilling process, including the voxel-based collision detection and the force evaluation. Section 4 presents the implementation results of the simulation system. Section 5 concludes the paper and discusses some future work.

II. COMPOSITE DATA STRUCTURE OF THE 3D MODEL

Human bone has complex structure, with cortical bone outside and cancellous bone inside. Cortical bone is composed of dense elements and is the strength to support the stiffness of the bone. Cancellous bone is constructed by sponge like structure and maintains a certain degree of flexibility of the bone. In the 3D modeling of the bone, the data structure should be able to represent these complex and inhomogeneous material properties.

Generally, surface-based modeling and volume-based modeling are both widely used in the realistic simulation. They both have some advantages and disadvantages. In the volume-based modeling, the data is naturally organized following the CT or MRI image sequence arrangement, and no interface extraction is required. Each voxel in the data can carry information such as color, density, opacity, material properties and so on. These information are particularly useful in the tissue model cutting, removing or deformation of the virtual surgical interaction. However, when the data topology is changed, volume rendering becomes very time-consuming, and the translucent effects also blur the boundaries of important structures leading to an unrealistic visual effect. Although this visualization artifact can be avoided by using a surface-based rendering. Nevertheless, the collision detection between two surface-based objects will be low efficient in the complex virtual scene with frequent 3D model structure changing, because the oriented bounding box tree used to separate the object space needs to be rebuilt once the model is changed.

To avoid the problems mentioned above, we intend to employ a composite data structure to represent the 3D model in the virtual scene. As shown in Fig.1, 3D model in our system is composed of the surface mesh with volumetric elements inside. The volumetric structure is reconstructed using volumetric rendering method. Voxel is a regular grid in the three-dimensional space of the object. In our simulation,

Fig. 1. Composite data structure.

each voxel contains the material properties and some other mechanical related parameters determined by the density and the physical conformation of the bone. Volumetric structure allows convenient update of the instrument position in the drilling process. Meanwhile, the surface mesh can be used for the fast and detailed rendering of the object.

In the modeling, the volumetric structure and the surface mesh should have physical connections, then these two structures can keep consistent during the changing of the model. Therefore, we specify the voxel on the boundary of the model as the vertices of surface mesh. Three neighboring surface voxels form a triangle of the mesh. If the volumetric structure is changed during the haptic interaction, the status of the voxel involved will be revised. A lot of new surface voxels appear and some other vanishes. For the voxel disappeared, the corresponding triangle will be removed from the mesh. In the other side, new triangle should be generated by searching for the neighborhood around the new voxel. This method is very flexible for the situation with 3D model changing frequently.

III. SIMULATION PRINCIPLE OF THE DRILLING PROCESS

A. Voxel-based collision detection

Based on the composite data structure of the 3D model, we could employ the collision detection algorithm on the voxel samplings. The most famous voxel-based collision detection method is developed by William et al. from Boeing cooperation [8]. In this method, the static object in the virtual environment is represented by a spatial occupancy, which is called voxmap. In the voxmap, each element can be treated as a single voxel. The dynamic object is represented as a point shell, i.e. a collection of point samples on the 3D mesh surface. Each sample point is assigned with an associated inward normal to facilitate the feedback force computation.

This method works pretty well in the 3D object contacts without topology changing. However, in our simulation, we find that it always leads to the missing contacts of several voxels. Within two consecutive frame, the instrument has been traveling for a while and a part of it has already penetrated into the bone model. If the traveling distance is larger than the side length of one voxel, only checking the shell points on the instrument surface to determine the interactive region is not enough. Therefore, we make some improvements to this

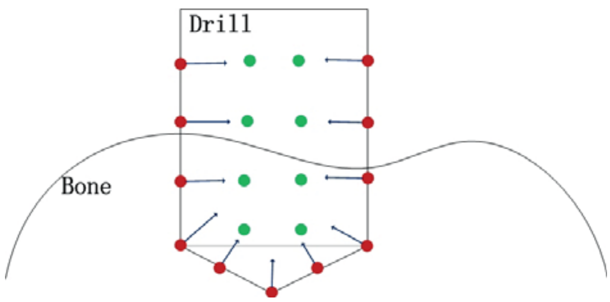

Fig. 2. Improved voxmap point shell method.

method. As shown in Fig.2, except the shell point (red color) on the surface, we also detect two other types of points. One type is the contacts between interior points (green color) of the instrument and the 3D model of the bone. For the other type, we sample the moving path line of each shell point and the sampling interval is chosen as the same as the side length of the voxel. Therefore, all the voxels swept and covered by the instrument could be located.

In our haptic modeling approach, the feedback force is mainly produced at the cutting edge of the drill. Therefore, only collision points on the cutting edge could be stimulation of the cutting force generation. The other sample points are used to determine the erosion area of the drilling process. All the voxels involved in the collision detection will keep absorbing energy to a certain threshold before being removed thoroughly.

B. Force evaluation

In our previous work [9], we illustrated the mechanical model used to simulate the haptic force generated during the drilling. However, in that work, the bone material is considered to be homogeneous. The real situation of the human bone is much more complex. Therefore, in this work, we will extend the previous model to be applicable to the bone material with inhomogeneous character.

We assume that the bone model is composed of two kinds of materials representing the cortical and the cancellous bone, respectively. Considering the oblique cutting of one cutting element on the material, as shown in Fig.3, the force acting on the element can be divided into two parts: one is the normal force of dF_n and the other is the friction force of of dF_f. In the drilling process, the blade may cut more than one kind of the material, thus the force computation can be write as:

$$dF_n = (K_{n1}t_1 + K_{n2}t_2)dw, dF_f = (K_{f1}t_1 + K_{f2}t_2)dw \quad (1)$$

where dF_n is the differential normal force perpendicular to the bone surface, and dF_f is the differential friction force produced on the bone surface during the cutting. Here, K_{n1}, K_{n2}, K_{f1} and K_{f1} are the specific cutting energy on normal and tangential direction for the two different materials of the bone, and their unit is $MPa(N/mm^2)$. t_1 and t_2 is the chip thickness, i.e. the depth of each cut, for the current cutting on the two materials. dw is the width of each cutting element. For the oblique cutting, dw equals to $dycos\tau$, where τ is the inclination angle. The multiplication of the chip thickness and the width of the cut represents the chip area of each cut. In mechanical theorem, the energy to cut a unit of the chip area is a constant. In our application, cutting element may cut two materials and the chip area is the addition of the two parts.

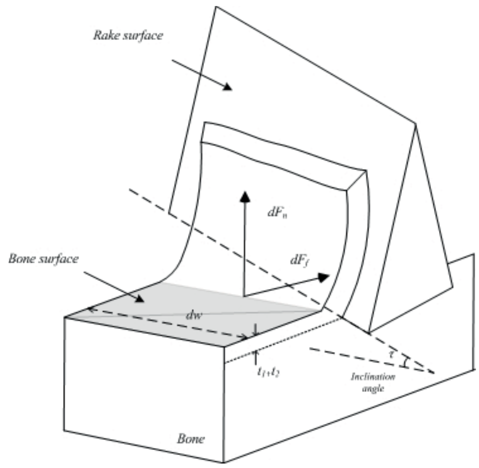

Fig. 3. Drill cutting on the inhomogeneous material.

In these equations, chip thickness $t(t1ort2)$ is a vital parameter. It directly affects the differential normal and frictional force. It equals to the distance that the cutting element moves on the plane perpendicular to the surface of the bone material being cut. Within a unit of time sequence, this distance is the feed per flute. In our simulation, drill with two flute is considered. Therefore, the chip thickness has rationale of $t = f_t/2 = U/(2\omega)$, where U is the velocity of the tool and ω is the angular velocity of the tool. From this equation, we can see that the chip thickness is also affected by the number of the teeth and the spindle speed of the drill. The larger the instrument's velocity is, the larger the cutting force will be. In contrast, if the spindle speed of the drill becomes larger or the drill has more blades, the user will feel a smaller force feedback on hand. The surgeon will feel hard to control the drill while using a large spindle speed because the force user can feel is too small and the material is removed too fast.

The equation (1) is written in the local coordinate, we still need to transfer it to the world coordinate. The transfer matrix is as follows:

$$\begin{aligned} dF_r &= -dF_n sin(\phi) + dF_f cos(\phi)cos(\psi) \\ dF_c &= dF_n cos(\phi)cos(\tau) + dF_f sin(\psi)sin(\tau) \\ &\quad + dF_f sin(\phi)cos(\psi)cos(\tau) \\ dF_e &= dF_n cos(\phi)cos(\tau) - dF_f sin(\psi)sin(\tau) \\ &\quad + dF_f sin(\phi)cos(\psi)cos(\tau) \end{aligned} \quad (2)$$

where ϕ is the rake angle, which is the angle between the rake face of the cutting element and the plane normal to the cutting velocity. ψ is the chip flow angle, which can be set the same as the inclination angle.

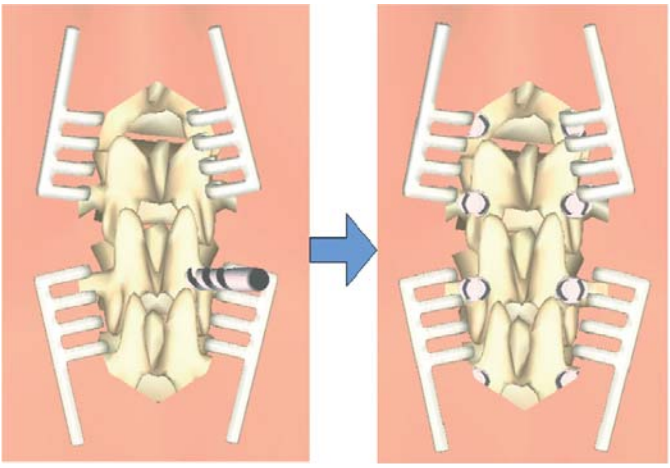

Fig. 4. Drilling simulation.

IV. Implementation result

The method described above is implemented in a bone drilling simulation system as shown in Fig.4. The graphical and haptic feedback are provided to the user to build a realistic surgical environment. In the system, we simulate the scene of the pedicle screw insertion surgery. As shown in left of Fig. 4, the drill is choosing the appropriate position to insert. After the drilling, screws are placed into the holes as shown in the right of Fig. 4. The computed forces are displayed by a Geomagic Touch Haptic Device in a refresh rate of 1KHz. The PC used to run the simulation is an Intel dual-processor 3.0GHz with 12GB of RAM.

V. Conclusion and future work

This paper propose a bone drilling surgical simulation. A composite data structure of the 3D model is proposed to facilitate the visualization of the model under frequent topology changes. An improved voxel based collision detection is presented to locate all voxels that have been swept by the instrument. Moreover, a haptic rendering method is developed to display the forces applied on inhomogeneous bone material during the drilling. In future, we will continually improve this simulator framework to make it as a useful training tool for surgeons. In particular, we will develop more specialties of the simulator to facilitate the training. Game-based learning is an excellent choice for this purpose, because its stimulating mechanism can attract the user to keep high frequent interactions with the knowledge and skills. We believe our simulator could be a very useful training system for orthopaedic surgeons in future.

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References

[1] Acosta, E. and Liu, A., Real-time interactions and synchronization of voxel-based collaborative virtual environments, IEEE Symposium on 3D User Interfaces, 2007.

[2] Morris, D. and Sewell, C. and Barbagli, F. and Salisbury, K, Visuohaptic simulation of bone surgery for training and evaluation, IEEE Transactions on Computer Graphics and Applications, 26(6):48-57, 2006.

[3] Agus, M. and Giachetti, A. and Gobbetti, E. and Zanetti, G. and Zorcolo, A., Real-time haptic and visual simulation of bone dissection, Proc. IEEE VR, 209-216, 2002.

[4] Arbabtafti, M. and Moghaddam, M. and Nahvi, A. and Mahvash, M. and Richardson, B. and Shirinzadeh, B.,Physics-Based Haptic Simulation of Bone Machining, IEEE Transactions on Haptics,4(1):39-50, 2010.

[5] Tsai, M. D. and Hsieh, M. S. and Tsai, C. H., Bone drilling haptic interaction for orthopedic surgical simulator, Computers in Biology and Medicine, 37(12):1709-1718,2007.

[6] Liu, Y and Laycock, S. D., A Haptic System for Drilling into Volume Data with Polygonal Tools, The Eurographics Association, 2009.

[7] Palmerius, K. L., Cooper, M., and Ynnerman A., Haptic rendering of dynamic volumetric data, IEEE Trans Vis Comput Graph, 14(2):263-76,2008.

[8] William, A. M., Kevin, D. P. and James J. T., Six degree-of-freedom haptic rendering using voxel sampling, SIGGRAPH '99 Proceedings of the 26th annual conference on Computer graphics and interactive techniques, 401-408,1999.

[9] Liu, X. F., Wang, Q., Li, J. Y., Qin, J., Wang, W. M., Liu, L. C., Zhang, X. J. and Heng, P. A., Virtual pedicle screw insertion surgical simulation with haptic rendering, 10th International Joint Conference on Computer Vision, Imaging and Computer Graphics Theory and Applications, 2015.