Surgical Simulation of Blood Flow in Human Soft Tissues

Jayasudha.K, Mohan.G.Kabadi

Abstract*: *Virtual reality with surgery simulation has emerged is an interesting field of research in many surgical procedures likes planning, training and evaluation. To perform realistic and real time simulation of soft tissues on human skin is a challenging task. The need for real time surgical simulation requires clinical operations to be performed on human skin such as insertion of scalpel, cutting and bleeding. The popular approach to simulate bleeding is (CFD) computation fluid dynamics that has much more computational complexity. This paper mainly focuses on simulation of blood flow as a single blood spot in human soft tissues when a cut is being made with a surgical scalpel. The proposed framework uses Delaunay triangulation approach to simulate multiple layers of skin. Deformation of soft tissues is achieved using vtkDeformPointSet ( ) function. All these works are carried out in real time that not only reduces computational cost but also reduces topological complexity of soft tissues.

Index Terms*: *Cutting, Deformation, layers, Soft Tissues, Simulation, Scalpel.

I. INTRODUCTION

In recent years, there is an enhancement in surgical training and practice with the advent of new virtual reality technologies that reduces cost, improves educational quality and safety. In surgery simulation concept of blood flow mainly depends on forces applied on the surgical scalpel. To achieve this one should have the idea of principles involved in simulation of cuts, its implication as oozing of blood and scalpel movements. Many works has been carried out in these areas and are listed below.

II. RELATED WORK

A. Simulation of Cuts

In virtual reality environment simulation of surgical cuts encompasses topological modifications that are quite non linear and its underlying physics is also complex. The authors worked in this area are as follows: Lim et al.,[1] uses combination of imaging techniques like image mosaicing and view dependent texture mapping along with a novel algorithm to achieve simulation of surgical cuts. Westwood, J. D[2] proposes cutting techniques that involves single surface object, multiple surface objects along with volumetric meshes and hybrid meshes. Nienhuys et al.,[3] uses Delaunay triangulated approach for cutting single triangulated surface with single incision and multiple triangulated surfaces with multiple incisions. Bruyns et al.,[4] explains that arbitrary cuts can be made on single and layered surfaces built with tetrahedral objects. Also explains that various cutting tools are used for cutting such as scalpel, scissors and loop cuttery tools. Author Okamura et al., [5] uses two degree of freedom with force feedback haptic scissors for simulation of cutting in virtual environment. Bielser et.al,[6] discusses cutting with arbitrary incisions on tetrahedral meshes, where as Forest et.al., [7] proposes preservation of tetrahedral meshes by tetrahedral removal algorithm. Ganovelli et.al., [23] discusses topological modifications that can be done on tetrahedral meshes along with coupling of multiresolution approach based on particle systems. Nienhuys et.al.,[8] explains geometrical and topological changes in the meshes during cuts using linear FE deformation simulation. Serby et al.,[9] proposes cutting finite element mesh with no need of intermediate steps, also explains the problem of decreasing element size with the help of a new algorithm. All these papers uses hybrid meshes with outer surface built with fine grain triangulated mesh and inner surface with coarse grain tetrahedral mesh. With this approach visual performance will be enhanced but a major drawback is that it will have more computational cost due to thicker tetrahedral meshes.

B. Oozing of Blood

The simulation modeling of oozing of blood concept in 3D deformable model comprises of either equations of deformation with computational fluid dynamics or finite element modeling. Briers et al. in paper [11] uses LASCA called as Laser Speckle Contrast technique for monitoring and measuring velocity of blood flow. This technique does not use scanning process or computes power but able to produce a 2D map to measure blood flow. Figueroa et al.,[12] explains a model called linear membrane model along with deformation equations used to measure blood flow in vessel wall. These vessel walls are modeled based young’s modulus equations. Author Vignon-Clementel et al.[13] explains the pressure and flow of blood in heart using finite element approach. Also the lumped model of heart is modeled using navier-strokes equations. Wissler and Eugene[14] presents quantitative results with flow of blood in human forearm through equations, where as Rayman et al., [15] discusses flow of blood using laser Doppler flow meter in diabetic patients under the foot’s skin. In paper [16],Cooper

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et.al explains flow of blood in fore arms skin and muscle. Measurement of blood flow is done using plethysmograph that is filled with water venons. Ruocco et al., [17] studies blood flow in lower lips of skin in monkey and rat model using sensory and automatic fibers. All these work done illustrates the use of computational fluid dynamics with special focus in the area of mathematics. And therefore the drawback is that such schemes cannot be measured directly as they involve high degree of complexity.

C. Scalpel Movements

Clinical operations on skin such as deformation and cutting depends on the correct placement and position of surgical instrument, also depends on the forces applied onto the needle insertion. This section deals with scalpel movements and insertion procedures. Author Chentanez et al.,[18] explains insertion of needles making use of algorithms in deformable tissues, also visualizes steering of needles, where as Bhasin et al.,[19] also explains insertion of needles along with haptic interaction such that end user should feel he is penetrating the scalpel into the skin deeply. Okamura et al.,[20] discusses robot assisted surgery with different types of stainless steel needle tips and needle diameters fixed on 6-axis force sensor and forces are applied on a silicon rubber phantom. Different needle tips discussed could be cone, cylinder or triangular with the concept that skin ruptures depending on the decrease in pin head sharpness. Nguyen et al.,[21] uses HMI (Human Machine Interface) along with haptic system that involves new surgical procedure to evaluate surgical instrument. Author Bielser et al., [22] also discusses needle insertion forces and scalpel movements using haptic rendering in a different approach. Bielser uses ODE solver (Ordinary Differential Equations) to study interaction between haptic scalpel and tissue model. Deformation of tissue occurs when scalpel blade enters the tissue with some force exerted on to the scalpel. Therefore the external force (Fe) applied to the scalpel purely depends on the force applied on the plane (Fp) and force perpendicular to the plane(Fpp) as shown in figure1.

$$Fe = Fp + Fpp$$

Fe = external force, Fp = force on the plane, Fpp = force perpendicular to the plane.

Fig.1. Scalpel Forces

The framework discussed in this paper do not use any robot assisted surgery or haptic feedback system, but simulates flow of blood in multiple layers of skin using VTK (Visualization Tool Kit) useful for applications in virtual surgery. The work mainly focuses on utilizing VTK functions in simple terms to show simulation on modeling surgical instrument called scalpel, skin cutting and flow of blood as single red spot. Visualization tool kit is widely used in three dimension computer graphics also in image processing. It comprises of classes and objects based on OOP's (object oriented programming) concept. The input data sets are primitives, textures etc., and output data sets are render window. Input data sets are processes through data processing filters and output data sets are returned as files. The next section discusses methodology in carrying out these procedures in detail.

III. METHOD

Above mentioned papers gives a brief idea about the various works carried out in the field of surgical instruments and surgical cuts. In fact the simulation of flow of blood occurs when the scalpel enters into the human soft tissue model with deeper penetration. Figure 2 shows the structure of soft tissues consisting of three layers: epidermis, dermis and hypodermis finally connecting to muscles. First layer is called epidermis that forms a thin protective structure, is estimated to be 50-100µm thick [26]. Second layer is called dermis that is like cushion soft estimated to be 300-400µm thick. Third layer is hypodermis also known as subcutaneous that is little more thick, connected to muscles and it supplies nutrients to epidermis and dermis layers.

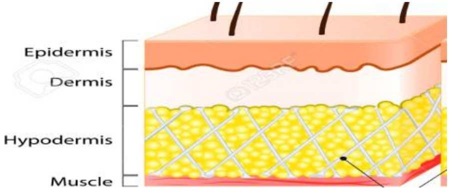

Fig.2. Structure of soft tissues

Figure 4 shows the flow of interaction of the proposed work. Initially the models of scalpel and soft tissue layers of human skin are formed in a pre-process step. Scalpel is modeled using basic vtk functions [29] and soft tissue layers are modeled using Delaunay criteria [28]. When the scalpel touches the layered model of skin, first collision detection takes place, next deformation of cells and lastly removal of cells[30].

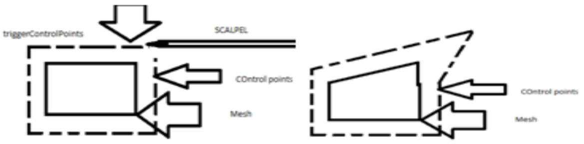

Fig.3. Deformation using control points

The three layers of skin are modeled using Delaunay 3D triangulation technique. Actually control points are created over mesh points. Then deformation is carried out using vtkDeformPointSet( ) function. This function deforms control points that in turn deforms mesh points as shown in figure3. Two variations are shown during scalpel penetration. One with little force and the other with more force applied to scalpel. When the scalpel is pierced with little force and when it reaches the epidermis layer and if it is taken out, it causes regaining the original model's shape demonstrates the true skin behavior. The other variation, when the scalpel is pierced with more force, the scalpel crosses the epidermal layer, reaches dermal layer and up on collision detection gives collision response causing deformation of cells.

As when the scalpel reaches the threshold limit, skin gets cut that means removal of cells takes place resulting in blood flow. The framework uses a simple vtk function called vtkSphere( ) to simulate flow of blood as a single drop and is texture mapped with red color to show blood as single red spot. Later when scalpel reaches the hypodermis layer only collision detection occurs without leading to deformation and removal of cells, this is because the hypodermis layer is connected to muscles, since muscles are hard and cannot be deformed. Next section discusses the experimental set up used to carry out the simulation.

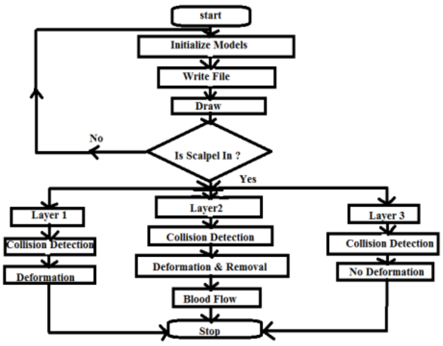

Fig.4. Flow of Interaction

IV. EXPERIMENTAL SETUP

The experimental set up starts with an initial display scene where medical individual should undergo proper training and practice to carry out skin deformation and skin cutting procedures. To simulate multiple layers of human skin, the medical individual should acquire cube data structure and scalpel. The cube data structures are implemented using Delaunay 3D triangulation technique[28] to simulate human skin layers. Figure5 illustrates the use case diagram that shows interaction between medical individual and the system. As when the scalpel interacts with cube dataset leads to next stage called collision detection further leading to deformation and removal stages. All stages are visualized using vtkRender( ) function in three dimensional view. Table1 shows implementation scenario with main actions taking place at all the stages.

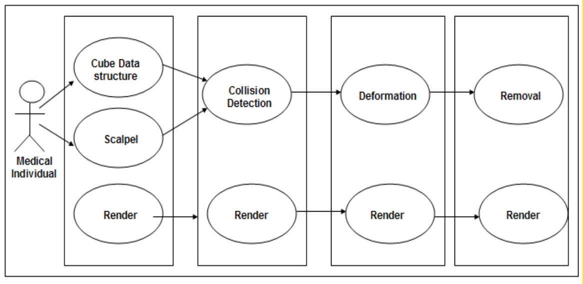

Fig.5. Use case diagram

TABLE I IMPLEMENTATION SCENARIO

Use Case	Scenario
Cube datastructure	Sets the dimension of cube
Scalpel	Sets the scalpel position
Render	Visualize the scene in 3D
Collision Detection	Detects the intersection of cube data set with scalpel
Deformation	Resize the intersected vertices of the cube data set
Removal	Remove the intersected vertices of the cube data set

The hardware and software requirement for developing this application requires high end graphics are listed as follows: Intel Pentium4 processor with minimum processing speed of 2Ghz, 4GB RAM, 1GB Graphics card and VTK(Visualization Tool Kit).The next section summarizes the results and discussions during deformation and removal stages.

V. RESULTS AND DISCUSSION

The multilayered surface of soft tissues along with virtual scalpel are modeled as a preprocess step [28]. The results are mainly based on the interactions taking place between the virtual scalpel and the multilayer soft tissues according to the flowchart shown in figure 3. The time taken to undergo deformation process and removal process at each layer were tabulated in table2 and table3. It is a known fact that collision detection takes less time for single surface and takes more time for multi layered surfaces. The reason behind this is scalpel has to intersect multiple primitives undergoing further search. Therefore the overall simulation speed depends on the interaction between the tool and the tissue. The deformation details are shown in table2, also the details during removal stage are shown in table3. Deformation takes place at epidermal layer alone and the same details are shown in table2. The epidermal layer is simulated as four adjacent cubes, with each cube containing twelve triangles based on Delaunay 3d criteria. As when the scalpel comes in contact with soft tissues, its intersection point is known, data gets modified at the adjacent cells i.e. interior levels of triangles in the array bounds. The memory location and the execution times are recorded. Execution time is in milliseconds, memory location of deformed cell points can be seen along with array bounds. The removal details are shown in table3, it depicts changes occurring at epidermal and dermal layers. This is because when the scalpel is pierced with little more force, it reaches the dermal layer causing removal of cells i.e. triangles. Dermal layer is again subdivided into superficial and deep dermis layers[27]. The epidermis layer is made up of four adjacent Delaunay cubes, therefore there are four rows in table2. Similarly dermis layer is made up of three layers of four adjacent Delaunay cubes, therefore there are twelve rows in table3. First four rows gives information about the execution time recorded in the epidermis layer, next four rows gives information about the changes happening in superficial dermis layer. Similarly last four rows gives information about deep dermis layer. The corresponding memory location along with minimum and maximum array bounds can also be observed in respective tables.

The following screen shots are shown below, the visual appearance clearly displays the changes occurring during insertion of scalpel. Initially the scalpel reached the epidermis layer when deformation of cells occur, reflecting the fact that epidermis layer is thin and soft. At any point of time when the scalpel is taken out, the model regains its shape reflecting the true behavior of skin. If the scalpel is pierced with little more force for the next time, it crosses the threshold limit and pierces the dermal layer. As the dermal layer is thick, cells i.e. triangles get transformed vigorously causing removal of cells. During this stage skin gets cut leading to slight oozing of blood depicted as a single red spot.

TABLE II DETAILS OF DEFORMATION

Name of Layer	**Array Bounds**		**Memory Location of Deformed Cell Points**	**Execution Time for Deformation of Cells(ms)**
	(Xmin, Ymin, Zmin)	(Xmax, Ymax, Zmax)		
Epidermis Layer	(0, 0, 0)	(20, 10, 20)	2A4FE10	0.304312
	(0, 0, 0)	(40, 10, 20)	2A50680	0.304313
	(0, 0, 0)	(60, 10, 20)	2A50E00	0.304314
	(0, 0, 0)	(80, 10, 20)	2A51580	0.304315

The multiple layers of skin with solid and wireframe models are shown in figure6(a) and 6(b). From the figure6(a) and 6(b) it is clear that there are totally four layers, first layer is epidermis, second and third layers are dermis layers divided in to superficial and deep dermis layers. The last layer is called hypodermis or subcutaneous layer, connected to muscles and bones. The entire model is simulated using Delaunay 3D triangulation concept [28]. Deformation process is shown in figure 7(a) and 7(b). The scalpel is pierced in to the soft tissue model to observe the changes. It is seen that there is a slight deviation in the internal structure of cells causing deformation.

TABLE III DETAILS OF REMOVAL

Name of Layer	**Array Bounds**		**Memory Location of Removal Cell Points**	**Execution Time for Removal of Cells**
	(Xmin, Ymin, Zmin)	(Xmax, Ymax, Zmax)		
Epidermis Layer	(0, 0, 0)	(20, 10, 20)	2A4FE10	0.308204
	(0, 0, 0)	(40, 10, 20)	2A50680	0.308205
	(0, 0, 0)	(60, 10, 20)	2A50E00	0.308206
	(0, 0, 0)	(80, 10, 20)	2A51580	0.308207
Superficial-dermis Layer	(0, -10, 0)	(20, 0, 20)	2A369F0	0.308208
	(0, -10, 0)	(40, 0, 20)	2BA9D10	0.308209
	(0, -10, 0)	(60, 0, 20)	2BAA580	0.30821
	(0, -10, 0)	(80, 0, 20)	2BAAD00	0.308211
Deep-dermis Layer	(0, -20, 0)	(20, 0, 20)	2C54C70	0.308212
	(0, -20, 0)	(40, 0, 20)	2C555D0	0.308213
	(0, -20, 0)	(60, 0, 20)	2C55C60	0.308214
	(0, -20, 0)	(80, 0, 20)	2D112E0	0.308215

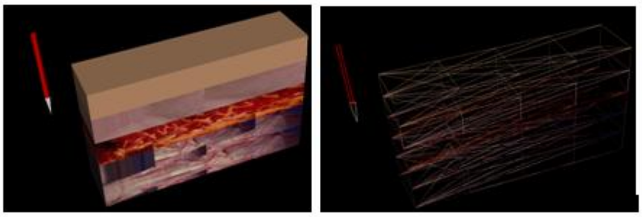

Fig.6. Layered skin with scalpel: Solid model(L), Wireframe model(R)

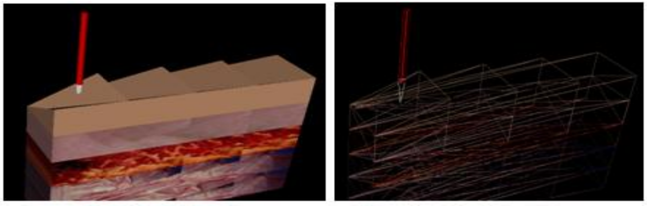

Fig.7. Deformation stage:Solid model (L), Wireframe model(R)

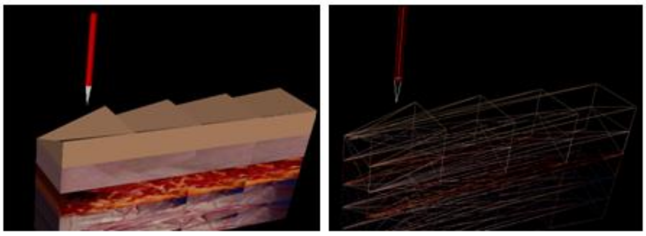

Fig.8. Scalpel taken out: Solid model (L), Wireframe model(R)

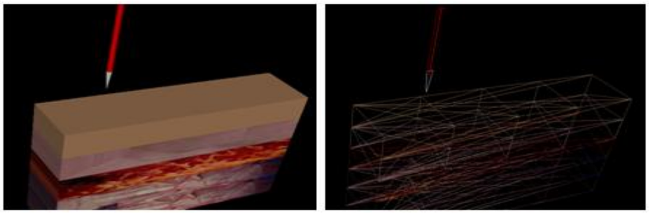

Fig.9. Shape regaining stage: Solid model (L), Wireframe model(R)

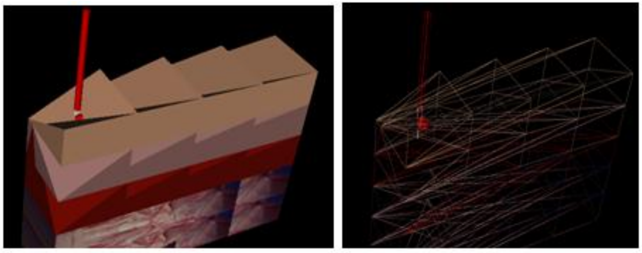

Fig.10. Blood flow from epidermis: Solid model (L), Wireframe model(R)

The scalpel is taken out to and changes are observed. Figure 8(a) and 8(b) depicts the screen shot when the scalpel is taken out, it is observed that when the scalpel is taken out the model regains its original shape depicting the true skin behavior without causing any damage to the internal structure of cells.. that means re-meshing is performed by repositioning the vertices of cells.

The entire process is repeated to for the second time. When the scalpel reaches layer1 deformation of cells takes place, when it reaches layer2 removal of cells takes place. That means the intersecting triangles are removed from epidermis layer. Once if the cells are removed, blood flows out from the skin indicating that the scalpel has reached the threshold limit. Blood flow from epidermis is depicted as a red spot shown in figure 10(a) and 10(b). The expansion of cells is also observed in superficial and deep dermis layers. Single drop of blood is simulated using built in function vtkSphereSource ( ) which is texture mapped to red color to depict blood spot. The process is continued until the scalpel reaches the hypodermis layer, even though collision detection takes place at this layer, no changes are seen. This is because the last layer is connected to muscles and bones. Also it is a known fact that muscles and bones are not deformable on their own. The conclusion part is discussed in the next section.

VI. CONCLUSION

Long back from seven decades, the researchers are studying the flow of blood in deformable 3D models. Different approaches were used for their study like FEM (finite element method), ALE (Arbitrary Lagrangian Eulerian methods) and reduced geometries. The flow of blood in deformable 3D models also depends on insertion and sharpness of the needle. The framework describes simulation of cutting and bleeding in a simple manner using visualization concept. The method do not encompass any haptic feed back system but proves the concept of deformation, cutting and bleeding using straight line incision. The overall concept reveals that deformation process occurs on epidermal layer of triangulated mesh, when it is taken out model regains the shape. Again when little more force is applied, crosses threshold limit leads to skin cutting stage followed by droplet of blood to visualize wounded skin. This framework might not support for large complex meshes. To enhance the capabilities of present work, it can be further expanded to include blood vessels and nerves into the model, can also use haptic feed back system or tracked virtual reality devices, necessary particle flow algorithms can also be included to depict motion of blood flow.

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Publications: Presented 8 technical articles in national and international journals. Also presented 6 papers in national and international conferences.

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