Soft Tissue Modeling Techniques in Surgery Simulation

Aruni Nisansala*, Maheshya Weerasinghe,G.K.A.Dias, Damitha Sandaruwan, Nihal Kodikara
University of Colombo School of Computing
Colombo 7, Sri Lanka
*Email: asn [AT] ucsc.cmb.ac.lk

Abstract—**Modeling and simulating the live tissues is a very complex and challenging process as it requires a huge amount of hardware power and advanced algorithms to be run on real time. There are number of articles, books and research papers which describe the properties of the different anatomy structures. This tissue modeling quality differs ranging from surgery types: neurosurgery, heart surgery, abdominal surgery, plastic surgery, minimal invasive surgery etc. Deformation accuracy and the computation time are the two significant constraints in soft tissue modeling for surgery simulation.**

Thus it has identified in the surgery domain the required surgery types can be categorized under three major heading which are surgery panning, Surgery training and scientific analyzing.

Here with this paper it is intend to compare and contrast the soft tissue modeling techniques and categorized them according to the surgery types.

Keywords-component; Soft tissue modelling, Surgery types, Accuracy, Efficiency

I. INTRODUCTION(HEADING 1)

Medical surgery plays a significant role as a public health strategy in prevention of death and chronic disabilities. According to the findings of Debas et al. it is shown that the absolute burden of surgeries are in its highest in southern Asia followed by the Western Pacific and Africa [1]. Several research [1] [2] has highlighted the public health is a global issue which should attain the concern of all. As the urge of surgery is growing the next arising question is whether there are enough human, financial, clinical resources to cope with the demand. This is a vital issue which needed to be addressed properly and efficiently. Likewise surgery performance is a high risk assignment which needs a precise training and sound knowledge. Even the experienced surgeons need continuous training to undergo critical surgeries.

Experiential learning has a direct impact on reducing the risk and high rate of successful surgeries. Medical domain training is one of the costly, time consuming and also a risky process which deals with another life. Hence the training process cannot be hinder or neglect carelessly. Practicing on living/dead animals (such as pigs, dogs, goats, and sheep), cadavers, mannequins etc. has been the training method before the virtual reality is bought to the medical surgery training domain [3] Numerous drawbacks were there with those training platforms. Especially the animal anatomy differs from the human anatomy so this training has to be done under various assumptions. Training on animals raise many ethical issues and this has already been banned in some European and North American countries. Same issue occurs with using cadavers. Dies tissues and organs do not simulate the liveliness, pulsing and blood pumping. Hence the realism is hindered within all those platforms.

With the advancement of the technology the complexity of the surgeries could be minimized up to some extent. Minimal invasive technique is one of the techniques which have being introduced in surgery domain which has a low risk engage. In MIS technique access to the patients' body is significantly degraded and it has reduced the patient stay in hospital, infection and also the morbidity. Training of these laparoscopic surgeries is done using training boxes, mannequin and so on. Unlike the open surgeries, minimal invasive surgeries have a high potential in recreating the scene in virtual environment. Surgeon gets only a video feedback of the abdomen and has to react according to that. Video surgeries such as laparoscopy, endoscopy, and etc. has been simulated and provided as promising training platforms.

II. SURGERY SIMULATIONS

During the past few years research and development on computer related surgeries has forged an exciting partnership between surgeons and the machines such as computers and robots, allowing users to train and polish their skills in better way [4]. Introduced Computer Integrated Surgery systems is highly capable of addressing the resource shortage in surgery training and planning.

According to the Satava et al the surgery simulators can be categorized into three major generations as showed in figure 1 [5].

The first generation of the medical simulators has only considered the geometrical nature of the human body. Applying virtual reality concept of navigation and immersion to tridimensional anatomical datasets was there. Regardless of its limited user interaction many amazing applications were implemented focusing the educational and training aspects.

The second generation has given its priority to integrate physical interaction of each anatomical structure. This generation has focus on kinematic constrains and muscle deformation. The deformation of soft tissue and its propagation to its neighbor tissues are some of the example which has acquired within thin simulations.

The third generation is focus on sophisticated modules. The anatomy, physics and physiology interaction with each other in different levels are simulated in this third generation. This was gained through developing functional anatomy that links the anatomy anatomical and physiological behavior of the body [7]. The features of the cancer developing tissue and its region, propagating pressure on one tissue and interaction with the model of chest cavity and lungs under forces are some scenarios which have been simulated in this.

Physical modeling of human tissue requires a huge research effort. To develop the second and third generation of simulators involves this soft tissue modeling. To preserve the realism deformation of the soft tissue needed to be incorporated. Modeling soft tissue is significant despite of the surgery type since the human body is mainly build up with it.

III. Surgery Types

Computational efficiency and the accuracy are the main two constrains which need to be addressed without compromising. To achieve the accuracy complex calculations have to be done. It is time consuming. If the accuracy is focused then the real time effect is compromised. Due to this there are several types of surgical simulators, implemented concerning this. In surgery planning the accuracy is essential. Surgery planning is done for predicting the outcome of the surgery. This also requires less computational time to perform several trails with different procedures. Scientific analyzing requires an accurate model as they aim to prove hypothesis or implement new procedures for surgery. But in a training simulator the real time interaction is the main feature which needs whereas the accuracy is not the primary concern. The following figure shows the accuracy over computational time of these three types of simulators [5].

A. *Surgery Simulator Architecture*

Surgery Simulator architecture can be categorized under three main components; input device, surgery simulator or the processing and the output. Especially the second generation simulators follow this hierarchy as they tend to provide user interaction and better realism. Operator should get the force of rotation, translation of the tools to perform and initiate the procedure.

With the haptic device interface user allow to feel that forces in surgery simulators. High fidelity haptic devices integrated with simulator have provided a better platform which enables user machine interaction in highly acceptable manner. Commercial force feedback devices are available in the current market guarantying variety of features such as the degree of freedom, size of the workspace, the provided force and torque, the shape of the end effector and price [8].

Collision detection, geometric modeling, physical modeling, haptic rendering, virtual rendering and processing are the main activities engage in the core of the simulation. Modeling the geography, detect the collision and behavior of the model relative to the user input and displaying the deformation is time consuming and it requires a huge amount of computational power. To overcome this barrier, researches have proposed various soft tissue modeling algorithms and techniques.

Finally the simulator needs an advanced user interface that includes visual and force feedbacks. Especially in the minimal invasive surgery context this force feedback interface is vital in order to make the correct decisions to proceed with the surgery.

IV. Soft Tissue Modelling

In general modeling the three dimensional model is based on medical images such as CT scans, MRI images, 3D ultrasound images and etc. With the advancement of the technology quality of this medical images have been heightened and also with the computerized tools today modeling the structure has become somewhat easier. This task has been more profound with the dataset provided by the National Library of Medicine in 1995 [9].

A. *Soft Tissue Modelling Constraints*

Despite of the surgery type it is essential to model the realistic soft tissue models. There are few constraints which should overcome in soft tissue modeling. Acquiring a precise soft tissue deformation is one of the limitations. Here it is significant to have a quantitative knowledge of the biomechanical behavior of the tissues. Number of studies has been done to recover quantitative parameters causing the deformation of tissue [10] [11]. Many studies were focus on skin [12], vessel [10], muscle, brain and heart. Then again impact of the deformation accuracy varies with the simulator type. For a training simulator the accuracy is a less priority. Hence the realism could be handled by compromising the accuracy of deformation.

Soft tissue interaction with its neighboring tissues, bones or the surgical tools is another constraint in modeling. Collision detection and computation of interaction forces are the two categories where this limitation occurs. Here the surgical tool is considered as the static body and the tissue as a deformable moving mesh to detect the collision. When detecting the collision it should be done real time. But it requires high computational time. Computational complexity is not sufficient with current algorithms for real time processing as it should concern self-collision and the external collisions. Alternative soft tissue representations have been proposed to address this limitation.

Real time deformation, cutting and suturing, force feedback computation, visualization are some other constraints which need to be addressed with care.

B. *Deformable Tissue Model*

During the past years many research work has led to many algorithms and techniques in deformable tissue modeling.

1) *Surface Volumetric Models.*

The geographical representation of the deformable body is consisting of either volume or surface. Selection between the surface and volumetric model differs by computer efficiency and physical efficiency factors. Since surface model has fewer vertices than volumetric models, it is computationally efficient. Surface models tend to give physically invalid deformation especially in the thin regions. Volumetric models are better suits to the cutting and suturing simulations as they provide geometrical and physical nature operations. Surface models are better in representation dimensional structure or two dimensional structures. This dimension simplification caused to speed up the computation. Tubular surfaces are normally represented as splines. But deformable volumetric structures such as livers are represented with their surface envelop. Deformation caused by liquid or gaseous pressure can be modeled with the volumetric models.

Spline and patches are being introduced in computer aided geometric design (CAGD) to numerically specify curves and surfaces. β-spline curves or surfaces are geometric design elements which stem from the well-known B-spline representation [13]. Bezier functions, double quadratic curves, patch coons, B-spline functions, rational B-spline β-spline functions, and NURBS(non-uniform rational B-spline) are some of the techniques used for designing smooth surfaces. These methods can be used to represent both planar and 3D curves. In generally spline technique is a parameter based representation system. It is computationally efficient and greatly supports the interactive modification. In some cases for a simple adjustment many control points are needed to be changed. Precise specification or modifications cost huge amount of work is the disadvantage in spline methods.β-spline is an example functions that provide an easy, simple, convenient and efficient way to create, generate and modify smooth surfaces of the model.

Free Form Deformation is one of the general methods for modeling the deformable objects. This provides more powerful level of control than controlling single point. This FFD technique can be applied in many different graphical representations such as polygons, splines, parameter patches and points [14]. The basic FFD method has extended by several research works [15] [16].

2) Spring and Particles.

Due to the rapid improvement of computer graphics capabilities and computer power, research on ‘physics based deformable tissue modeling’ was accelerated. Mass spring system is one of the physically based techniques used widely to model deformations. An object is modeled as a collection of point masses connected by springs. Newtonian laws of motion are used to simulate the dynamic behavior in MSS.

$$\vec{F}_{net} = \frac{d^2}{dt^2}(m\vec{u}) = \frac{d}{dt}(\vec{p}) = \frac{d}{dt}(m\vec{v}) = m\vec{a}$$

Differential equations such as Euler, Runge-Kutta are used to solve the deformation in each node by discretization of time in time steps. All the friction, gravity and damping coefficient forces applied on P_i can be integrated through time by a simple Euler method and it would allow computing the force on $P_i$at any time t as follows.

$$F_{total} = \sum(k.\ \Delta x) - v(t).d + F_{external}$$

MSS require minimal computation power comparing to the continuum mechanics based methods. The underlying physics is simple with well implicit dynamics. Models implemented using MSS can be animated at rates not possible with other methods. Real time interaction is well maintained in MSS based models. Since most of the real time simulations are based on MSS.

Even though MSS is advantageous in those aspects, since it lack of volumetric information this does not allow cutting which is significant in surgery simulations. Rapid propagation is not allowed in MSS and it also does not allow accurate modeling of heuristic determined material properties and oscillations. When a spring constants are large problems could be occur with MSS. Large springs are used to model objects that are nearly rigid or rigid. Despite of those drawbacks MSS is used in Medical and Engineering domains where the perfection is not a must.

MSS is widely used in facial animation to model human expressions [17] [18]. Different spring constants were used to model the different tissue types based on their properties. Craniofacial simulations are one of the common simulations which use MSS [19]. Not only the deformable tissues MSS facilitate modeling wide variety of objects including cloth, hair and deformable solid [20]. Nedel and Thalmann carried out an extensive research on simulating muscles using springs. Elasticity was enhanced using theory of elasticity, especially concerning linear spring and Hooke’s spring theory to calculate the force produced by linear springs. In this research they have simulated muscles only by their surfaces not the volumetric details which could save the computing time [21].

Linked volume is the technique of adding volumetric information to the MSS. It is much demanding as it requires increased number of nodes. This will represent the volume of the deformable object evenly spaced cubic elements that are commonly interconnected using springs and dampers [22]. In this each element is linked to its nearest six neighbors. The links are free to stretch, contract and shear when the elements are deformed, deleted when the objects are cut and created when the objects are joined [22].

3D Chain mail algorithm is a novel algorithm introduced based on the linked volumetric representation. This is also used in several medical simulations since it allows the fast propagation of deformation. In chain mail list is maintained with each elements current position and old positions. When a selected element is moved its old position and element indicator is updated in the list of moved elements. Accordingly its neighbours in top, left, right and bottom are added to the lists of candidate for movement. The lists of candidate elements are processed until the entire candidate list are exhausted. The candidate lists are processed in right, left, top, bottom order. It begins with the first element in the list. The element is moved until it satisfies the stretch and shear constraints between sponsoring element and the list element. New positions calculated as follows [23],

if (x - xleft) <minDx, x = xleft + minDx;

else if (x - xleft) >maxDx, x = xleft + maxDx;

if (y - yleft) < - maxHorixDy, y = yleft - maxHorixDy;

else if (y - yleft) >maxHorixDy, y = yleft + maxHorixDy;

Mass tensor models are another extension of the mass springs. In this approach volume is represented as tetrahedral using simple linear relationship to describe deformation. Both spring mass model and tensor mass model have the same computational complexity which is linear in the number of edges. Even though tensor mass has a slight advantage in computation as it does not have any square root calculations. The tensor mass is not applicable for large displacements.

3) Continuum-mechanics-based methods.

a) Boundary Element Method

Mass tensor models are another extension of the mass springs. In this approach volume is represented as tetrahedral using simple linear relationship to describe deformation. Both spring mass.

b) Finite Element Method

FEM is computationally demanding technique but will provide with accurate deformations. As the computational overhead this is hard to adopt in real time simulations. There are several techniques used to speed up the computations of the FEM. Mass lumping and time integration is frequently used with FEM with single processor. The finite element method allows high accuracy on two dimensional and three dimensional objects.

4) Method: Comparison of the Deformable Soft Tissue Modeling Algorithms

Some of the important algorithms and methods are categorized in the following table [22] [24] [25]. To achieve the target of the paper categorizing the soft tissue techniques according to the surgery types it require to analyses the characteristics of each algorithm.

TABLE I. COMPARISON OF THE DEFORMABLE SOFT TISSUE MODELING ALGORITHMS

Base Category	Method Name	Characteristics
Heuristic Methods	Mass Spring System (MSS)	•Newtonians laws of motion are used to simulate the dynamic behavior. •System of differential equations is solved for every node by discretization of time in time steps (using Euler and Runge-Kutta). •Disadvantages [24]: □ Lack of volumetric information does not allow for simulating cutting □The central difference scheme is used as the integration method caused drawbacks in mesh handling. □MSS does not allow accurate modeling of material properties which are heuristically determined and oscillation may occur
	Linked Volumes	•This is a volumetric representation of MSS which represent the volume of the deformable object with same spaced cubic elements. •More computationally demanding as the increased nodes and the interconnectivity. •Propagation of the deformation is slow down.
	Chain Mail Algorithm	•In this algorithm it discretizes the volume although the interconnection of the cubic elements is represented as links of chain. This link can moved freely and it affect to the neighbors in limited range •Force responses are assumed to be proportional to the penetration depth, thus non-homogeneous tissues are not properly modeled.
Continuum Methods	Boundary Element Method	•BEM evolved from integral equation methods known as Boundary Integral Equation Methods (BIEMs). •With some restrictions and assumption on the deformable body BEM can be used for research focusing the viscoelasticity and non-homogeneous properties in soft tissues [25]
	Finite Element Method (FEM)	•This allows discretize irregular geometries •This method has a high computational overhead for real time processing and memory. •Mass lumping and time integration are some well-known methods to speed up the computation which are used in FEM with a single processor [26][27]
	Finite Difference method	•When the geometry of the object is regular this approach could be use accurately and efficiently.

Base Category	Method Name	Characteristics
		•This is a fast approach for real time applications using linear models. As cutting requires offline calculations this cannot be modeled.
	Finite Fast Element	
Multi resolution approaches		•Different level of details is applied to the mesh. High resolution is applied to the deformation areas. •Selection of active tetrahedral, online re-meshing and refinement throughout the simulation are common tasks done in this kind of approaches [28]

C. *Surgery Types vs. Soft Tissue Modeling Techniques*

As mentioned in above section there are three types of surgery types and according to the type the required simulation properties are being vary. Under this topic the intention would be to classify the soft tissue modeling techniques and identify them with relevant to the surgery type.

In surgery training the efficiency or the real time feedback is a must. Without real time feedback the user reality could not be maintained. In this category the efficient algorithms has to be used. To maintain the accuracy it requires solving complex algorithms in real time. But with the limitation of hardware and processing power the real time computation is bit hard. But as a training platform this simulation category can compromise the accuracy to gain real time interaction. Mass spring algorithm, Chain mail algorithm and linear algorithms provides the best solution in this.

The surgery planning category requires both accuracy and real time performance up to some extent. The accuracy should be there because the surgery plans are done with the ultimate target of performing the scenario in live surgery. Compromising the accuracy in this scenario would result endangering someone’s life. The performance should have a considerable efficiency to perform more than one planning within the time. Because if one procedure would not satisfy the surgeons intentions they have to redo the process and asses it. Here both efficiency and accuracy matters more than the other two surgery types. Hence as the soft tissue modeling techniques it is better to use such algorithms which would safely give the both aspects of accuracy and efficiency. The extended chain mail algorithm, hybrid models based FEM are some of the algorithms which can tackle this problem of securing both accuracy and efficiency.

In scientific analysis the most required parameter would be the accuracy. Here the intensions are to provide with a hypothesis by simulation the surgery. Hence the accuracy factor should be higher than on any other case. Due to that in this type of simulations, it could compromise the efficiency or the real time feedbacks. With considering that it is necessary to select the highest accurate modeling techniques based on continuum such as FEM, BEM and their modified versions.

TABLE II. SURGERY TYPE AND RECOMMENDED SOFT TISSUE MODELING TECHNIQUES

Surgery Type	**Recommended Soft Tissue Modeling Type**
surgery training	Mass spring algorithm, Chain mail algorithm , linear algorithms
surgery planning	Finite Element Method, Boundary Element Method
scientific analysis of surgery	Extended chain mail algorithm, hybrid models based FEM

CONCLUSIONS

With the literature review and related works it is clear that the soft tissue modeling has its constraints and required to be explored thoroughly to select the relative technique to model live organs. Soft tissue modeling algorithm are being drastically modifying and changing in order to compete with the advanced hardware. By that the real time user interactivity and accuracy has been achieved in to some extent.

With the complexity of the surgery type the required soft tissue quality parameters varies. By selecting the proper algorithm which fulfills the requirement of the surgery type it would enhance quality of the whole simulation environment. For the fact if FEM is selected to be developed for a surgery training platform it has to pay more than enough hardware/processing power and even it would not be able to achieve the real time interaction to satisfy the user realism. Here it requires selecting an algorithm which gives real time feedbacks more importantly than the other factors. Likewise according to the requirement of the surgery type the soft tissue algorithms should be selected and integrated in the simulation environment.

REFERENCES

[1] Haile T Debas, Richard Gosselin, Colin Mccord, and Amardeep Thind, "Surgery," Disease control priorities in developing countries, pp. 1245-1260, 2003.

[2] Stephen Bickler et al., "Key Concepts for Estimating the Burden of Surgical Conditions and the Unmet Need for Surgical Care," World Journal of Surgery, pp. 374-380, 2010.

[3] Xiaojun Shen et al., "Haptic-enabled telementoring surgery simulation," IEEE Multimedia, pp. 64-76, 2008.

[4] Taylor Russell H, Stephane Lavallee, Grigore Burdea, and Ralph Mosges, "Computer-Integrated Surgery: Technology and Clinical Applications," Clinical orthopaedics and related research, pp. 5-7, 1998.

[5] Hervé Delingette, "Towards Realistic Soft Tissue Modeling in Medical Simulation," Proceedings of the IEEE, vol. 86, no. 3, pp. 512-523, 1998.

[6] Hervé Delingette and Nicholas Ayache, "Soft Tissue Modeling for Surgery Simulation," Computational models for the human body, pp. 453-550, 2004.

[7] Douglas DeCarlo, Jonathan Kaye, Dimitris Metaxas, John R Clarke, and Bonnie L. Webber, "Integrating Anatomy and Physiology for Behavior Modeling," Interactive Technology and the New Paradigm for Healthcare, vol. 18, 1995.

[8] Timothy R. Coles, Dwight Meglan, and Nigel W. John, "The role of haptics in medical training simulators: A survey of the state of the art," IEEE Transactions on Haptics, vol. 4, no. 1, pp. 51--66, 2011.

[9] Michael J Ackerman, "The visible human project," Proceedings of the IEEE, vol. 86, no. 3, pp. 504--511, 1998.

[10] YC Fung and SC Cowin, "Biomechanics: mechanical properties of living tissues," Journal of Applied Mechanics, vol. 61, 1994.

[11] Abe Hiroyuki, Kozaburo Hayashi, and Masaaki Sato, Data book on mechanical properties of living cells, tissues, and organs.: Springer, 1996.

[12] Wayne F Larrabee, "A finite element model of skin deformation. I. Biomechanics of skin and soft tissue: A review," The Laryngoscope, vol. 96, no. 4, pp. 399--405, 1986.

[13] W. Annicchiarico, G. Martinez, and M. Cerrolaza, "Boundary elements and B-spline surface modeling for medical applications," Applied Mathematical Modelling, pp. 194-208, 2007.

[14] Sarah F F Gibson and Brian Mirtich, "A Survey of Deformable Modeling in Computer Graphics," Merl - a Mitsubishi Electric Research Laboratory, pp. 1-31, 1997.

[15] Sabine Coquillart, "Extended free-form deformation: a sculpturing tool for 3D geometric modeling," vol. 24, no. 4, 1990.

[16] Ron MacCracken and Joy Kenneth I, "Free-form deformations with lattices of arbitrary topology," Computer graphics and interactive techniques - ACM, pp. 181-188, 1996.

[17] Stephen M Platt and Norman I Badler, "Animating facial expressions," ACM SIGGRAPH computer graphics, vol. 15, pp. 245-252, 1981.

[18] Keith Waters, "A muscle model for animation three-dimensional facial expression," ACM SIGGRAPH Computer Graphics, vol. 21, no. 4, pp. 17-24, 1987.

[19] Erwin Keeve, Girod Sabine, Ron Kikinis, and Bernd Girod, "Deformable modeling of facial tissue for craniofacial surgery simulation," Computer Aided Surgery, vol. 3, no. 5, pp. 228-238, 1998.

Tiantian Liu, Adam W. Bargteil, James F. O'Brien, and Ladislav Kavan, "Fast simulation of mass-spring systems," ACM Transactions on Graphics, vol. 32, no. 6, pp. 1-7, 2013.

[20] Luciana Porcher Nedel and Daniel Thalmann, "Real time muscle deformations using mass-spring systems," Computer Graphics International Proceedings, pp. 156-165, 1998.

[21] Alejandro Granados, "Haptic Deformable Shapes Using Open Source Libraries," MSc Thesis 2008.

Shoichi Kobayashi and N. Nishimura, Boundary Element Methods: Fundamentals and Applications.: Springer Science & Business Media, 2013.

[22] Sarthak Misra, "Realistic tool–tissue interaction models for surgical simulation and planning," Hopkins University, Doctor of Philosophy dissertation submitted to The Johns dissertation Hopkins University 2009.

[23] Sarah F Gibson, "3D ChainMail: A fast algorithm for deforming volumetric objects," in Proceedings of the 1997 symposium on Interactive 3D graphics.: ACM, 1997, pp. 149-154.

[24] Faraci Alessandro, "A Multi-resolution Nonlinear Finite Element Approach to Real-time Simulation of Soft Tissue Deformation with Haptic Feedback," Department of Surgical Oncology and Technology, Imperial College London, Doctoral Dissertation 2009.

[25] Xunlei Wu, Michael S. Goktekin, and Frank Tendick, "Adaptive Nonlinear Finite Elements for Deformable Body Simulation Using Dynamic Progressive Meshes," in EUROGRAPHICS, 2001, pp. 1-10.

[26] Adam W. Bargteil, Chris Wojtan, and Jessica K. Hodgins, "A Finite Element Method for Animating Large Viscoplastic Flow," in SIGGRAPH, 2007, pp. 1-8.

[27] Ehsan Dehghan, Xu Wen, Zahiri-Azar Reza, Marchal Maud, and Septimiu E. Salcudean, "Modeling of Needle-Tissue Interaction Using Ultrasound-Based Motion Estimation," University of British Columbia and TIMC-GMCAO Laboratory, MICCAI, pp. 709-716, 2007.

[28] Paloc Celine, Faraci Alessandro, and Bello Fern, "Online Remeshing for Soft Tissue Simulation in Surgical Training," in IEEE Computer Graphics and Applications, 2006, pp. 24-34.