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Instrument-Tissue Segment Interaction Using Finite Element Modeling

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Abstract—**A virtual reality based laparoscopic surgery simulator is an important training option for laparoscopic surgeons. It has significant advantages over other training methods. Instruments-anatomy interactions are one of the main features of these simulators. In this paper we present the deformation of the uterine tube using three dimensional finite element methods with finite element software. The work examines the feasibility of incorporating the finite element (FE) model within the visual graphic model to achieve high degree of realism of instrument-tissue interactions.**

I. INTRODUCTION

A Principle aim of laparoscopic surgery is to reduce damage to the surrounding healthy tissue during surgery undertaken on internal organs. Laparoscopic procedures are performed by making small holes in the human body less than half an inch in length which act as the entry points for an endoscopic video camera and a number of surgical instruments. For the patient it reduces both recovery time and the risk of complications since it generates less scarring and reduces the healing time compared to open surgery. However for surgeons it is a complex procedure and requires specific training. Surgeons lose the direct view of and tactile contact with the operational site.

A number of new features need to be incorporated into the surgical simulation system before it can be implemented as a useful training option for endoscopic surgeons.

1. Modeling the entire operational surgical field to create an overall acceptable concept[1, 2].
2. The modeling of the interaction between instruments and anatomy needs to be undertaken[1, 2].
3. The user interface needs to be developed; so the user can undertake different manipulations incorporating different organs, and allowing immediate evaluation of performance[1].
4. The modeling of tissue needs to be sufficiently realistic, so that surgeons encounter nearly the same visual and tactile behavior as that of the real tissues.

Since the virtual environment includes both rigid and soft objects, these objects have to respond to contact with each other. The rigid objects such as virtual laparoscopic instruments must show rigid motion, while soft objects such as anatomical objects must show deformable motion. In addition some anatomical objects will need to show both rigid and deformable motion. The motion of virtual anatomical objects is brought about by their interaction with virtual instruments and other anatomical objects. Examples include grasping, pushing, cutting, tearing and suturing, and interaction between the virtual anatomical objects themselves.

The simulation system typically includes geometry modeling, physical modeling, computation modeling, collision detection, deformation, and surgical manipulation such as cutting, and rendering. Geometric modeling can be divided into a surface model and a volumetric model. The advantages of the surface model are its simplicity and computational efficiency. The problem is however that a surface model cannot simulate the interior structure of human organs. Some manipulations such as cutting need to simulate the internal structure of organs because there is interaction between the surface structure and the internal structure. A volumetric model can simulate the interior structure, and therefore might be more suitable to simulate cutting. Modification of a volumetric model is however complicated[3].

Many methods have been developed to model soft objects and these methods can be categorized as physically based models such as: finite element models, mass spring models, long element models[4, 5] and hybrid models. Non-physically based models are: free form deformation[6-8], splines and patches[9, 10].

To deform a geometric model so that it behaves in a realistic way requires the model to incorporate physical properties. Linear elasticity, incompressibility and nonlinear extension[11] are common physical properties upon which physical models are based. It has been reported that a FE method was applied to model tissue deformation for surgical simulation [12, 13]. A tetrahedral element with a linear interpolation function was used, and a number of pre-processing steps were performed to achieve real time simulation. Superposition and linearity of object deformation were assumed, and the deformations of all nodes were pre-calculated and stored for every surface node. This method improved the speed of the simulation [13].

This work has encouraged the authors to investigate the values of such methods in the context of a laparoscopic simulation. In our simulation the physical properties of soft

tissue were modeled as a linear elastic material.

II. METHOD

The finite element method is a way to solve continuum mechanics equations. The general expression of a finite element problem for a dynamic system of deformable objects is expressed by the discretised energy equation:

$$m\ddot{u} + d\dot{u} + ku = f \qquad (1)$$

where u is a 3n x 1 displacement vector of n nodes relative to the object's centre of mass, and m, d, and k are 3n x 3n mass, damping and spring stiffness matrices respectively. f is a 3n x 1 matrix of applied forces. The idea is to use a static linear system instead of a dynamic motion system by neglecting the dynamic part of equation 1 ($\ddot{u}$, $\dot{u}$), the equation becomes:

$$ku = f \qquad (2)$$

FE models achieve a discrete approximation by dividing the region of interest into elements. It can be used to describe both surface and volumetric models of deformable objects. For surface models quadrilateral (Quad) and triangular (Tri) elements were used as shown in figure 1 and compared to each other in terms of deformation realism and computation time. For volumetric models tetrahedral (Tet) and hexahedral (Hex) elements were used as shown in figure 2 and compared to each other. Each element connects only to neighboring elements via shared nodes. The deformation (and thus energy) for points within an element is interpolated from the element's nodes.

FE models compute deformation over the entire model instead of at discrete points. So that our approach is to compute deformation over a segment of the model instead of the whole model, and later on integrate the deformed segment into the whole model.
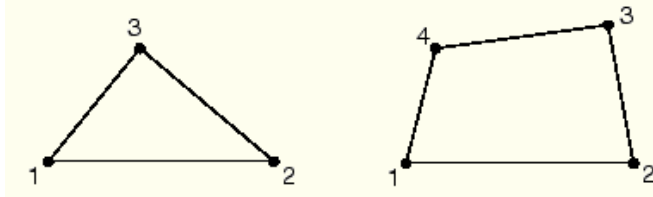

Fig. 1. Triangular element (left), quadrilateral element (right).
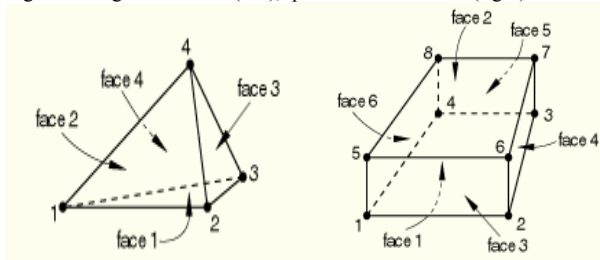

Fig. 2. tetrahedral element (left), hexahedral element (right).

We define the segment to be modeled as a three dimensional linear elastic object. A finite element model of the segment was developed using commercial finite element software (ABAQUS v. 6.6) [14]. The segment was modeled as a deformable meshed cylinder and was assumed to be linear elastic and isotropic. A simple mesh was created using different types of elements between the two tips of a grasper to analyze the grasping of soft tissue. The tips were modeled as an analytical rigid body with flat shape 15mm by 4mm.

The contact between the segment and the tips was modeled using surface to surface contact. The tips were considered as master surfaces and the tissue segment as a slave surface, since the tips are stiffer than the segment. A frictionless contact property was defined so that the tissue could freely slip between the tips. Then displacements were applied to the reference points of the tips that were initially oriented to the surface of the segment.

III. RESULTS

Figures 3, 4 and 5 show the deformation of the segment under the compression of the tips. This segment was meshed using 4 nodes tetrahedral element with 229 elements and 72 nodes. The analysis was performed on Pentium IV computer with two CPUs with speed of 2GHz and 1GHz of RAM. The computation time for the analysis was completed in 0.5 sec in six increments. Figure 6 shows the whole model in which the segment is integrated with the same computation time.

Figure 7 shows the deformation of the segment with 112 hexahedral elements. The analysis time was completed in 0.8 sec. By comparing it to the deformation of the segment with tetrahedral elements, it is obvious that the segment with tetrahedral elements is visually more realistic and computationally more efficient even though the segment with hexahedral elements has fewer elements. Figure 8 shows the comparison between the hexahedral elements and tetrahedral elements in terms of computation time. At small numbers of elements both models are computed in less than one second but as can be seen in figures 5 and 7, tetrahedral elements give less visual distortion. By increasing the number of elements the computation time also increases, but the tetrahedral element model is more computationally efficient than the hexahedral element model, even though they are approximately similar from the visual perspective.

Regarding the deformation of the segment with a surface based model, the deformation of the segment is approximately the same for triangular elements and quadrilateral elements as shown in figures 9 and 10. Computationally, they are nearly the same. However, the computation time of the either surface based model is less than the computation time of the volumetric based model.

The advantages of a surface model are its simplicity and computational efficiency. The problem is however that a surface model cannot simulate the interior structure of the tissues. Some manipulations such as cutting need to simulate the internal structure of organs because there is interaction between the surface structure and the internal structure. A volumetric model can simulate the interior structure, and therefore might be more suitable to simulate cutting.
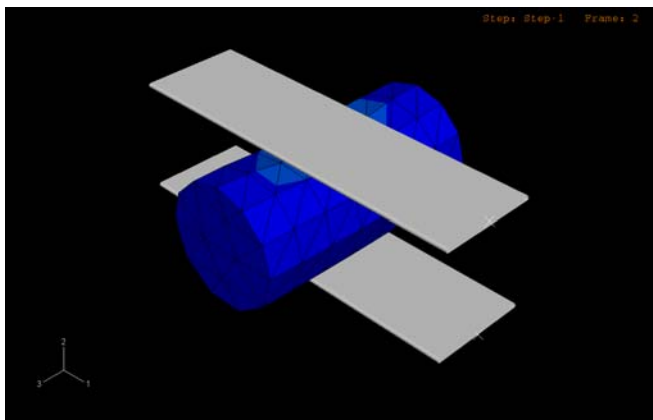
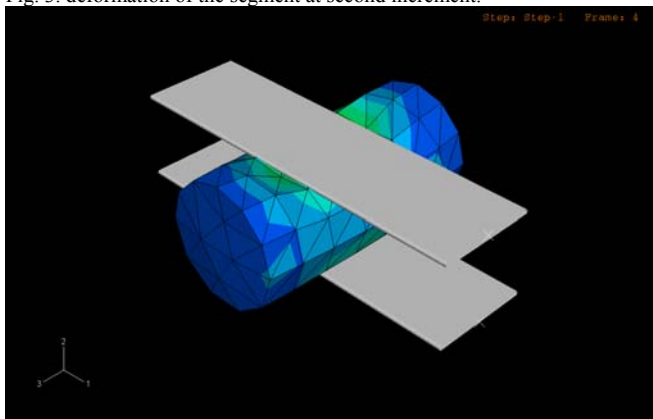Fig. 3. deformation of the segment at second increment.

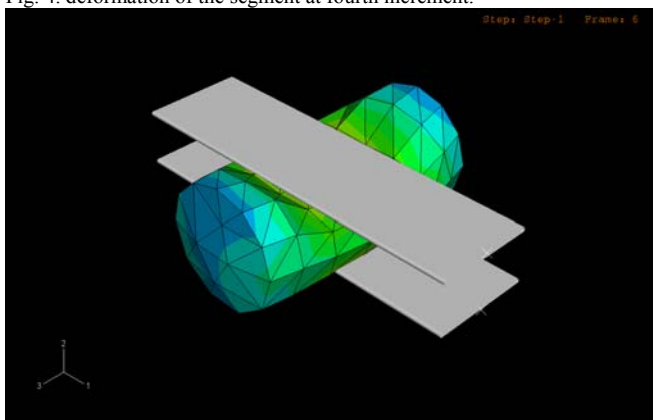Fig. 4. deformation of the segment at fourth increment.

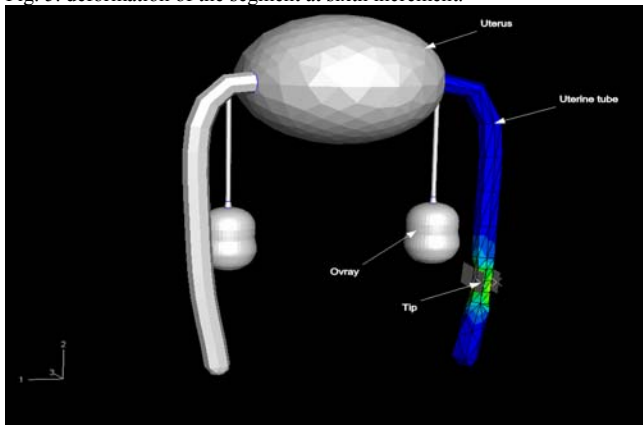Fig. 5. deformation of the segment at sixth increment.

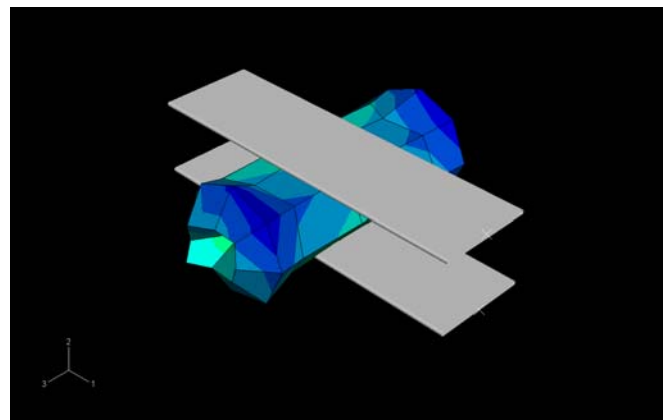Fig. 6. integration of the segment in the whole model.

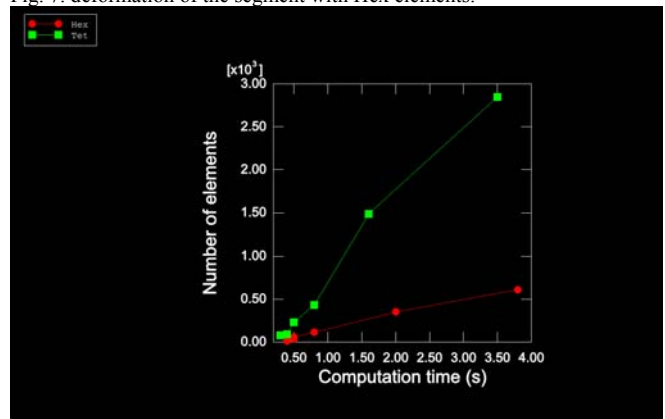Fig. 7. deformation of the segment with Hex elements.

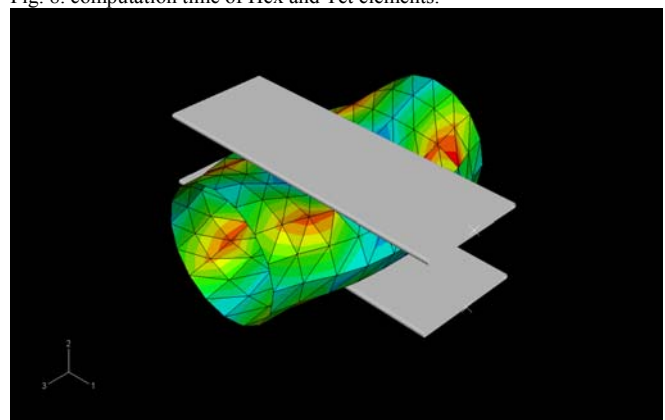Fig. 8. computation time of Hex and Tet elements.
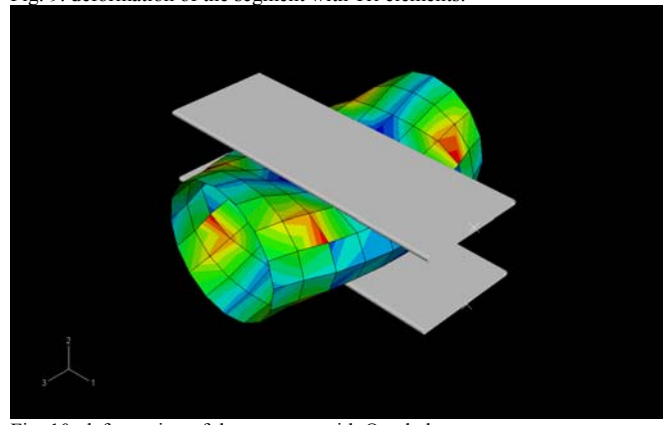

Fig. 9. deformation of the segment with Tri elements.

Fig. 10. deformation of the segment with Quad elements.

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IV. CONCLUSION

In this work we are investigating the role of finite element models in the representation of instrument-tissue segment interactions. Results presented represent grasper tips grasping a uterine tube segment. Other interactions considered include finite element modeling of cutting, diathermy and other deformations.

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