Development of a Microsurgery Training System

Fei Wang, Eileen Su, Etienne Burdet and Hannes Bleuler

Abstract— **Surgeons require significant training to acquire sufficient dexterity and hand-eye coordination to manipulate objects skilfully under the microscope. This paper presents a computer-based real-time simulation of microsurgery as well as the hardware setup. It presents a realistic physics-based elastic suture and blood vessel model, fast collision detection techniques, suture insertion process and novel approach of a haptic forceps. The simulation environment demonstrates a complete vascular suturing system to train skills such as grasping, suture placement, needle insertion and knot-tying running at 500 Hz, sufficient for physical realism.**

I. INTRODUCTION

Microsurgery is a general term for open surgery performed under a stereoscopic microscope with 5 to 40 times magnification. The most obvious procedure involves the anastomosis of blood vessels and nerves of typically 1 mm in diameter. Microsurgeons require significant amount of practice to acquire sufficient dexterity and hand-eye coordination to manipulate objects skilfully under the microscope. Due to the complexity of the procedures, extensive and on-going practice is crucial to maintain proficiency in microsurgical techniques. Basic skills and techniques are normally taught at microsurgical courses where trainees have the opportunity to work on animal tissues. The training time for such laboratory practice with supervision is extremely limited, after which, trainees mostly have to learn by observing senior surgeons or assisting some tasks in real operations. Concerns over patient safety, financial restraints in providing training materials and stricter rules concerning use of animals have restricted training even further.

Successful use of simulators in the aviation and nuclear industries has motivated research into virtual reality as an alternative for learning surgical procedures. Virtual reality systems not only offer the possibility of distributed practice for effective motor skill learning; they potentially provide reliable and systematic assessment and feedback to the trainees. Cases can be replicated and level of difficulty adjusted to suit the learner's capability. A few commercial systems for training minimally invasive surgery are now available in the market and studies on using these simulator systems in learning tasks have shown favorable outcome including transfer of skills from virtual reality to real operations [1].

The many perceived advantages of incorporating virtual reality systems in surgical training motivated us to develop a microsurgery simulator to train vascular anastomosis, a major task in many microsurgical operations. The simulation environment allows a complete vascular suturing training, while holding real forceps providing haptic feedback. Computational algorithm of this system incorporates physics-based elastic suture and blood vessel model, efficient collision detection and rendering techniques.

Organization of the paper is as follows. Section II gives a literature survey. Dynamic modeling of the suture and blood vessel are described in Section III, the structure of collision detection and insertion process in Section IV. A dedicated haptic forceps developed for this application is described in Section V, while the graphics and implementation with results constitute Section VI.

II. STATE OF THE ART

Anastomosis simulation has previously been attempted by only a few groups of researchers. Graham conducted a standardized program where subjects were required to place needle through a simulated vessel wall [2]. A group of new surgery residents and a group of medical students (novices) participated in this experiment and findings showed that there were significant improvements in day 3 compared to day 1 for the first group while second group showed significant improvements in group scores. Unfortunately, no details were given with regards to their simulator system, scoring system or experimental protocols.

Boston Dynamics Inc. developed a comprehensive simulator for vascular anastomosis and the system could distinguish between experienced and novice group based on different criteria [3]. This simulator is made up of surgical tools with force feedback provided by a pair of Phantom devices. A 3D graphical display shows physics based-computer simulations of the tissues and tools are projected onto a semi-reflective mirror and viewed using a pair of stereo goggles. The drawback of this system is that surgeons have to maintain a standing position with no proper arm support when practicing. The relatively large tools used correspond more to general surgery rather than to microsurgery.

A microsurgery simulator developed by Brown et al [4] utilized two real surgical forceps tracked electromagnetically. Their comprehensive software system allowed collision detection, determined interactions between microsurgical tools and modeled deformable object using mass-spring representation for tissue and constraint-based technique for suture. While this simulation provided rather realistic visual characteristics of materials, it lacked haptics due to the suture's

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geometry approach. Many may argue that microsurgery is dominantly visual, but haptics could play a role during learning, and to provide such capability to the system would allow more diverse training strategy on a virtual reality simulator. Motor learning studies suggest that learning performed in an unstable force field can reduce motion variability thus improve motion accuracy [5].

Similar to Brown's work, Holbrey et al developed a suturing simulator for vascular surgery [6], [7]. The Finite Element Method (FEM) was used to simulate deformable tissues instead of mass-spring model. A pair of ratcheted needle holder attached to a Phantom Desktop (Sensable Technologies) provided haptic feedback to the dominant hand while tissue manipulation in the subordinate hand was achieved using Spacemouse (3dConnexion). To detect the opening and closing of the needle holder, serially connected magnetic switch was used. To be able to effectively apply the system into general microsurgical environment requires taking into account the suture dynamics and interaction with deformable tissues.

Although these studies have proposed different kinds of real-time models and hardware setup, realistic visualization and dynamic modeling integrated into a complete system, taking into account sufficient details is still a challenging task in terms of computational cost and performance. Our work follows that of Holbrey in the sense that haptic feedback can be provided but differs in computational algorithm in tissue representation and additionally offers suture manipulation and knot-tying. A lighter solution is also applied to measure the opening and closing of the forceps.

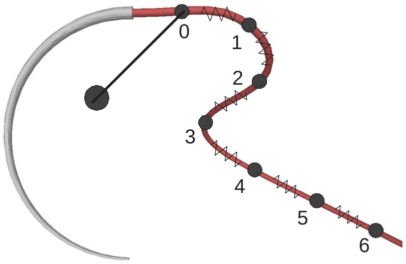

Fig. 1. The structure of a suture model

III. MODEL DYNAMICS

A. Dynamic Thread

We have developed a physics-based thread model for medical simulation. The model takes into account Newton's laws and considers the main properties of a real thread, such as stretching, compressing, bending and twisting, the effect of gravity as well as contact forces due to self-collision and interaction with the surgical tools. Based on this model, realistic knot tying is realized at haptic rendering rate. The topological structure of the suture is represented by a list of $K+1$ nodes with 4 DOF $i \in \{0,1,\cdots,K\}$ at positions $\{\mathbf{x}_i = (x_i^1, x_i^2, x_i^3)\}$ and at torsion angles $\{q_i\}$ connected by K links (Fig. 1). A mass m_i and a polar momentum of inertia I_i are assigned to each node i. A group of (massless) linear and angular springs attached to each link produce stretching, compressing, bending and twisting between and on the nodes. The dynamics of each node i is determined by:

$$\tau_i = I_i \cdot \ddot{q}_i(t) \qquad (1)$$
$$\mathbf{F}_i = m_i \cdot \ddot{\mathbf{x}}_i(t)$$

Torsion force τ_i applied along the thread is due to stretch and friction:

$$\tau_i = \tau_i^s + \tau_i^r \qquad (2)$$

$\mathbf{F}_i$ is the sum of external forces applied on mass m_i:

$$\mathbf{F}_i = \mathbf{F}_i^s + \mathbf{F}_i^b + \mathbf{F}_i^t + \mathbf{F}_i^r + \mathbf{F}_i^c + m_i\,\mathbf{g} \qquad (3)$$

where $\mathbf{F}_i^s$ is the force resulting from *stretching and compression* of the spring links connected to node i. The *bending force* $\mathbf{F}_i^b$ computed from two angular springs with minimum bending radius at nodes $i-1$ and $i+1$. $\mathbf{F}_i^t$ is the force resulting from *twisting* of the link which is proportional to the stiffness constant of the angular spring. *Dissipation* enters the system in the form of friction forces, $\mathbf{F}_i^r$. The *contact force* with the environment is $\mathbf{F}_i^c$, and $m_i\,\mathbf{g}$ is the *gravitation force*.

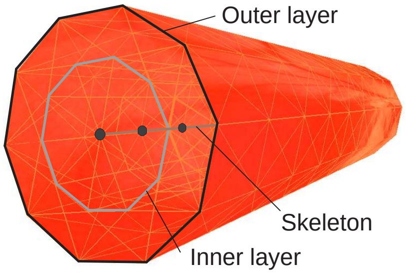

Fig. 2. The structure of a blood vessel model

B. Blood vessel

Similarly we represent the blood vessel by a double layer of 3D mass-spring mesh connected by a skeleton in the center (Fig. 2). The inner and outer layer represent the thickness of the vessel. A group of nodes connected with springs are evenly distributed along the layers. There are also springs to connect the outer layer, inner layer and skeleton. The skeleton has similar structure as the suture, with stronger bending and twisting stiffness to prevent the vessel from bending and twisting like a soft rope.

The model dynamics are computed at each time step while the haptic devices are manipulated. Firstly we read the positions and orientations of the haptic devices. Next, we refresh the collision detection and compute the total external force and torque applied on each node. This force can be fed back to the haptic device through the node in contact. Finally the motion equation is Euler integrated at each node.

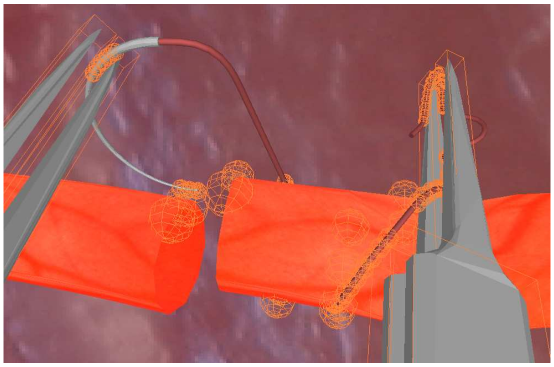

Fig. 3. A collision scene

IV. COLLISION AND INSERTION PROCEDURES

In vascular suturing simulation, a suture often collides with itself or other objects such as surgery tools, vessels etc., as shown in Fig. 3. As our dynamic model requires a reaction force, every collision must be detected at every time step efficiently.

The bounding-volume hierarchy method (BVH) [8], [9], [10] constructs a hierarchical bounding representation by arranging the bounding volumes into a tree structure. The hierarchies help to quickly discard large subsets of the object primitives that are too far apart to possibly collide.

We enwrap the vessel surface, the needle and suture volume with spheres and surgical tools with axis-aligned bounding boxes (AABBs) respectively. As the linking sequence of our deformable model is fixed, the BVH topology is pre-computed once at the beginning of the simulation and remains fixed, only the center and radius of each bounding sphere need to be updated when the model deforms. A recursive algorithm is used to compare the binary trees of the needle and suture against each other. The intersection depth is found for each collision pair of primitives, where the reaction force increases exponentially with this depth.

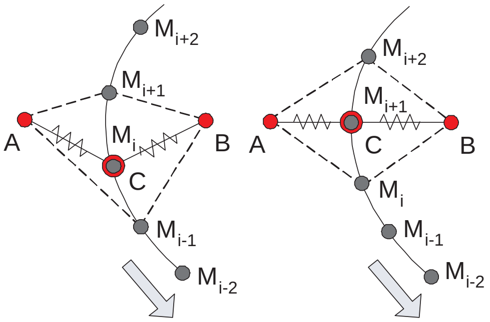

Fig. 4. Needle and suture insertion

Needle and suture insertion is a tricky procedure in vascular suturing. A 2D case is shown in Fig. 4, where the needle is penetrating the vessel surface, the vessel node C will follow the initially closest needle node M_i. When the spring length of AM_{i-1} is much bigger than AM_{i+1}, the vessel node C will leave the needle node M_i for the next node M_{i+1} and we start to compare the length of AM_i with AM_{i+2}.

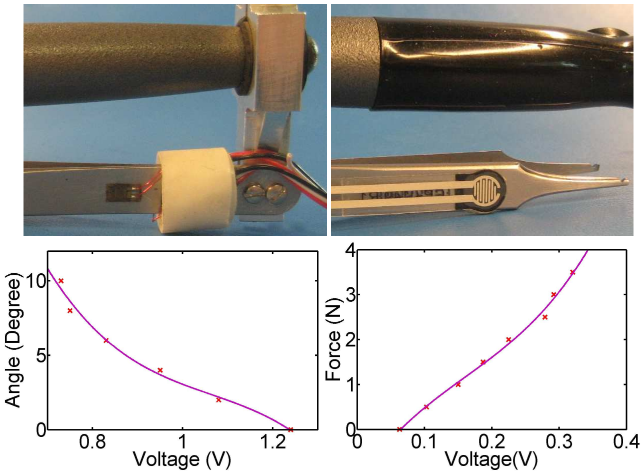

Fig. 5. A real surgical forceps is mounted to the stylus of Phantom Desktop. One side attached with a strain gauge (left) and the other side with a pressure sensor (right). The below plots show the fit to measurement of voltage at different angles (left) and voltage to a pressure applied on the sensor (right).

V. HARDWARE SETUP

The hardware setup of this microsurgery trainer includes using a pair of real surgical forceps mounted to the stylus of Phantom Desktop (Fig. 5). On each forceps, a strain gauge is attached to one of the forceps blade and a pressure sensor to the other blade.

The strain gauge is used to measure deformation (strain) as we close the forceps while the change of the resistance of the strain gauge let us accurately detect the opening angle of the forceps. In our application, the strain gauge has a great advantage over other approaches such as potentiometer, optical distance sensor and magnetic coil, because of its extremely tiny size and light weight. Thus it will not interfere with the natural feel of forceps manipulation.

The pressure sensor is used to measure and record the applied grasping force during suturing, as we plan to analyze the correlation among grasping force, accuracy and tremor.

A bridge circuit and amplifier are used to measure the voltage changes (Fig. 5), from which the opening angle and grasping force can be predicted.

VI. IMPLEMENTATION

The simulation is implemented on a DELL INSPIRON 9400 laptop with Intel Core 2 Duo 2.0GHz CPU, a NVIDIA GeForce Go 7900GS 256M GPU and 2G RAM. The suture is modeled with 100 nodes and 99 links. The blood vessel is modeled with 168 nodes and 889 links. Each forceps is represented by approximately 100 triangles for collision detection. The dynamic model is updated at 500Hz and graphics is updated at 30Hz. As shown in Fig. 6, the simulation provides a realistic VR environment to help the surgeon in training of microsurgery procedures.

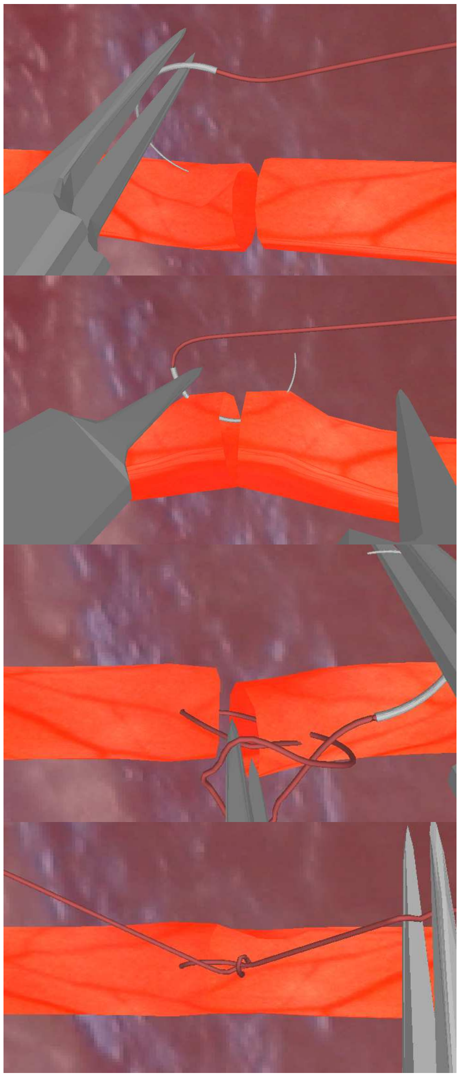

Fig. 6. Key steps of vascular suturing

VII. CONCLUSION

This paper presented a realistic physics-based elastic suture and blood vessel model, fast collision detection techniques, suturing process and novel approach of a haptic forceps. The dynamic suture model follows Newton's laws and considers the main properties of the suture, such as bending and twisting, as well as contact forces due to the interaction with the surgical instruments. The blood vessel model uses a skeleton and a double layer structure to realistically represent local and global deformation. An efficient collision detection algorithm allows update rates compatible with very high haptic demand and provides continuous high quality force feedback.

In addition a novel haptic forceps was developed to interact with the virtual environment and measure the grasping force applied by the thumb during the operation. The simulator integrates internal and external forces within a single framework, it overcomes limitations in realism of systems without haptics. The simulation environment demonstrates a complete vascular suturing system to train skills such as grasping, suture placement, needle insertion and knot-tying.

In the future, we would improve the dynamic model using Cosserat theory [11] and design appropriate training tasks. We intend to provide additional force feedback such as learning cues to speed up the learning curve. Experiments will be conducted to determine correlation among grasping force, accuracy and tremor.

VIII. ACKNOWLEDGMENTS

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