Literature review for haptic simulation in surgical training

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***Abstract*—In the last few years, haptic simulations for training purposes have attracted considerable attention. They allow to increase the number of sensory channels used during the learning phase, to reproduce different scenarios and to repeat the same operation multiple times. Some medical tasks are especially useful to be reproduced in simulation, since they must be executed often. This literature review has the purpose of studying some of these tasks, such as needle insertion, hernia palpation, incision and suture. A special focus is given on the possibility of performing these tasks with the provided haptic device (which is the Geomagic Touch) and with the provided software (which is the Sofa Framework).**

Index Terms – Haptics, Surgery Simulation, SOFA Framework, Geomagic Touch.

I. Introduction

Most medical procedures involve the use of tactile sense to feel and manipulate tissues and body parts. In order to acquire the sufficient experience needed to perform the procedures correctly, students must repeat the same operation multiple times.

This implies that practice is key when it comes to learning the right motor skills needed by doctors and surgeons [1]. For this reason, various teaching options have been tested throughout the years (such as animals, mannequins, VR) but all of them have some drawbacks, one of them being failing to emulate the real human body feeling. A possible optimal training alternative can be found in haptic devices coupled with visual simulations. They allow to interact with the virtual environment by having both a visual and a tactile feedback, thus increasing the number of sensory channels through which doctors can learn.

They offer a virtual environment that can show multiple real-case scenarios with different levels of difficulty, and allow the user to repeat the same operation multiple times.

In particular, haptics in the medical field usually recreate the kinesthetic touch ([2]), such as forces and torques, that are usually sensed in the muscles, tendons, and joints. To do so, the structure of the haptic device is usually that of a graspable grounded device that allows the user to push on it (and be pushed back) through a hand held tool. An example of graspable hapic device used in the medical simulation field is the Phantom Omni, which is also the one that will need to be used in my project.

There are multiple tasks that can be simulated with a haptic device. The literature review will focus on some of the following tasks that can be performed on the skin: needle insertion, suturing, incision and palpation.

II. State of the art

The first section of this paper will cover the state of the art of the skin and tool models. The next sections are instead dedicated to the study of the medical task that are normally reproduced in simulation due to their usefulness.

A. Skin and tools models

1) The 3D models: In order to perform any kind of simulation, the physical simulated model of the skin and of the tools must be developed. This implies, as the first steps, defining the 3D model of the objects and developing an algorithm that computes the successive positions and velocities in time and space of the object's points.

The basic approach is the discretization of the volume in sub models to easily solve computational mechanics. This approach must be used for the *skin*. In particular, in the literature two methods can be found: the Finite Element Method (geometry-based) and the Mass Spring System (physics based).

FEM is based on the discretization of the domain into subregions (elements). It comes from approximating a continuous function by a discrete model composed of a set of piecewise continuous functions which are deformed over a finite number of subdomains called elements.

MSS is similar to the finite element method, in the sense that the object is divided into smaller elements: the surface boundaries and the volume of an object can be divided into meshes. Unlike in finite element method, there is no continuous interpolation function defined. Instead, a particle mass is assigned to each vertex of the element and a spring and damper are set along each edge to connect the pmass particles. This models has been mostly used to represent the contour of a volume. It is similar to wrapping a 3D object with a 2D cloth or membrane.

LeDuc et Al. ([3]) model the skin as a linear mass-spring model in which they also place home springs to bring mass particles of the tissue back after displacement. In order to integrate the positions of the nodes after a displacement they use Euler's method under a quasi-static approximation to Newtonian physics.

Payandeh and Shi ([4]) also use a mass spring approach and a simple iterative explicit Euler method to update states of soft tissue.

Comas et Al ([5]) implement a CUDA-based nonlinear FEM into the SOFA open source framework, which is the program that I am going to use. They imposed the non linearity by the choice of an anisotropic visco-hyperelastic model.

Together with the different methods for discretization, the number of skin layers also varies: Jayasudha et Al. ([6]) implement three layers (epidermis, dermis, subcutaneous layer) while Moreau et Al. ([7]), as well as Yang et Al. ([8]), implement one layer only.

Regarding the *needle*, multiple simple models can be found in literature.
Payandeh and Shi ([4]) use a curved needle (suturing needle) while Choi at Al. ([9]) use a straight model. In general, the main idea is to use multiple segments: this kind of modelling makes it is possible to accurately identify which part of the needle is locally in contact with the tissue by checking the collisions of the single part ([9]).
A literature research was made for the scalpel, but results were very similar to the ones of the needle so they are not reported here.

Some *thread* models can be found too.

LeDuc et Al. ([3]) model the thread as segments linked with springs. The home spring coefficient is set to Kh=0 so that it moves with the rest of the skin. Cylinders are superimposed to the segments for a better visual effect.

Similarly, Payandeh and Shi ([4]) model it as a sequence of mass points linked by springs and Choi at Al. [9] use a sequence of segments linked by spherical joints.

Lenoir et Al ([10]) represent the thread curce as splines, using Catmull-Rom splines for their interpolation property and uniform cubic BSpline for their better continuity which makes them better for simulation.

2) The collision detection models: After modelling the object, collision detection between objects must be taken into consideration too. If there was no collision detection, virtual objects would penetrate each other and give no force feedback to the haptic device.

As for the physical model, collision detection is also based ont eh idea of discretization, so that the collision can be detected on submodels instead of on the entire surfaces. This is usually done by filling in or covering the target objects as tightly as possible with bounding volumes. Not only the collision is checked on the surface of these simple geometric structures that surround the object ([4], [11], [12]), but the checking is made by following a specific hierarchy: from the outer (bigger) elements to the inner (smaller) ones. The bounding volumes of the hierarchy can have different shapes. Both bounding spheres ([4], [11]) and bounding boxes are very common ([12]) but the choice of the shape strongly depends on the shape of the object itself. The number of volume also depends on it and on the available computational power.

B. The medical tasks

1) Needle insertion into soft tissues: The needle insertion can be divided into three different steps: pre-puncture, puncture, complete penetration. Each step produces different forces ([7], [13], [8]) that are analyzed in the following.

Pre-puncture phase: There is a stiffness due to the elastic properties of the skin, which is distorted but doesn't get pierced yet. In the literature two main mathematical models of forces can be found for this phase.
An example of mathematical model for the forces can be a second order polynomial of the type $F(x) = a_1x + a_2x^2$ (Okamura et Al. [14], [13], Yang et Al [8], Jayasudha et Al [6]) to recreate a non linear effect, where: x is the needle displacement, d1 is the maximum displacement before skin is cut, a1 and a2 are constants to be determined (in [8]: a1=0.0019, a2=0.0499 and in [14]: a1=0.0480,a2=0.0052, and a1=0.0020,a2=0.0023).

Choi et Al ([9]) develop a different approach for this phase. The idea is that two requirements must be met: the needle tip is in contact with the tissue, and it is moving in a way such that the direction of its velocity is crossing the axis of the needle at an appropriate angle θ. After a threshold distance inside the skin, the skin is considered punctured. The force is then a resistive force that prevents the needle from entering the tissue and it is considered to be linearly proportional to the needle's penetration.

Puncture and post-puncture phase: The forces acting in these phase are ([7]):

- Cutting force: Yang et Al. ([8]) calculate this force by measuring the total force at this phase and substracting the frictional force.
- Friction force: Asadian et Al. [15] address it with a Lugre model, a dynamic model based on the microscopic representation of irregular contact surfaces and elastic bristles. Similar models are used in other articles ([16],[13]).
- Clamping force: this force is used by Kikuuwe at Al. [17] and their model is used also by Moreau et A.l. ([7]). This force acts on the side of the needle shaft in the normal direction by the tissue that surrounds it and constrain the needle's movements. It is implemented as a virtual fixture.

A different approach for this phase is the one opted by Choi at Al. ([9]). In order to constrain the needle to stay on or move through the collided tissue element, an anchoring spring is created by using a distance joint to anchor the needle segment to the centroid of the tissue element. It prevents the thread from slipping through the tissue element, essentially modelling the frictional force between the thread and the insertion point. The frictional force that resists the needle and the thread from sliding is modelled as a constant.

Moreover, Moreau et Al. address this phase with a tracking-wall approach ([18]). This method consists of implementing a virtual wall that follows the needle's position, with a small position difference between them, to ensure a constant force during the injection. Once the needle stops its progression, the wall is smoothly updated to the needle's last position.

Complete penetration: in this case the only force that is present is the friction force, which can be modelled as in the previous step. For example, it may be written as a Fourier series [8].

2) Hernia palpation: There are few papers about this medical task performed with the Geomagic device. This is because it would need a different force feedback on each finger, and the device only allows one point of feedback. For example, Ullrich and Kuhlen ([19]) adapt the haptic devices with pads to provide real sensations. They perform dragging of the tissue and studied the forces that are generated by using bimanual station of Geomagic Touch. They enable the use of two fingers (minimum number of fingers used during palpation according to the doctors).

3) Incision: This kind of simulation an be done with either surface or volumetric models. Volumetric (usually tetrahedra) are complex to handle when modified, but surface models cannot display the object's interior structure to show the result of a cut. Another difficulty is that users of surgical simulators expect to see the result of cutting as they move the instrument, without noticeable delay. Re-meshing is needed for this and must be performed as the cutting tool travels along its path. Here are reported some examples of incision found in the literature.

Zhang et Al. ([20]) create a MSS of the skin with tetrahedral surface mesh and additional meshes built in runtime to simulate depth. They implement different methods for cutting: pierce-in, slide-in: cut-into, cut-through. Two different primitives of the skin are defined after cut through has ended.

Zerbato et al ([21]) create a MSS of the skin that is based on matrix that stores: positions, force and mass (update lasts 3ms). They move the calculations to the GPU. and define different methods for interaction: probing, grabbing, cutting. In particular, when cutting is done, they simply disable the spring contribution in that position.

Gutierrez et al ([22]) create two different models (superimposed on each other) by doing a XFEM / FEM model remapping. When collision is detected between the scalpel adn the skin, they check for collision in the nearby tetrahedra. Visually, the internal meshes are created by connecting intersected points on the tetrahedra that have been cut. They use the Sofa framework and the Geomagic plugin.

4) Suture action: This is another typical medical task that can be simulated. It requires movements in the 3D space, so it exploits the 6 dof of the Geomagic Touch device and is therefore well suited to be simulated with it. Its simulation usually requires a patch of skin, a needle, a thread, and two haptic devices. Here are reported some examples of suture found in the literature.

LeDuc et Al ([3]) treat one of the nodes as a hole and connect this node to one of the nodes of the suture. When applying force to the suture, since the node of the suture is joined to a node of the object, the two move together as one, and the rest of the object gets pulled along with it.

Payandeh and Shi ([4]) model the suture as a MSS that consists of a sequence of mass points laying on the centerline of the suture connected together by various types of spring. The skin moves with suture if friction with suture is greater than spring force on node. Otherwise, it slides along suture. They also add an example of unwanted event such as the ripping of the tissue, to make the simulation more realistic. TThey use a bimanual station of Geomagic Touch.

Choi et Al ([9]) model the interaction needle-skin as described in the needle insertion chapter. They use a bimanual station of Geomagic Touch.

Finally, Sung et Al ([23]) do not give a detailed description of their suture action, but they explain that they simulate five different suture procedures, by breaking the action into steps, which is good for both teaching and developing the simulation. They use a bimanual station of Geomagic Touch.

III. Conclusions

After analyizing the state of the art of these medical tasks simulations and how they can be done with the geomagic device, I restricted my options to Stuture and Incision only. The reason for excluding the Needle insertion option is because it is hard, with the Geomagic Touch device, to actually perceive the diffenrent kinds of forces relative to the skin layers. The reason for excluding the hernia palpation is instead because it is impossible, with one device only, to allow a different force feedback to the fingers of the user. It would be possible to do so just by using two devices with 3D printed pads and a support for fingers, but I excluded that hypthesis. On the other hand, both incision and suture exploit the potentialities of the Geomagic, since they need 6dof to move in the space. Moreover, I believe they are very interesting to simulate from a collision and visual point of view.

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