Literature review on 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 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 studies some of these tasks, in particular: needle insertion, hernia palpation, incision and suture. A special focus is given on the possibility of performing them with the haptic device and software that will be used in my thesis project (and which are, respectively, the Geomagic Touch and 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. For this reason, various teaching options have been tested throughout the years (such as animals, mannequins, VR) but all of them have some drawbacks such as failing to emulate the real human body feeling.

A possible optimal training alternative can be found in haptic devices coupled with virtual simulations. This kind of simulation allows 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 also 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.

The structure of the haptic device is that of a graspable grounded device that allows the user to push on it (and be pushed back) through a hand held tool. This recreates the kinesthetic touch (forces and torques that are usually sensed in the muscles, tendons, and joints). An example of a very common haptic device used in the medical simulation field is the Phantom Omni.
In particular, the aim of my thesis is to create a surgical haptic simulation to be used as a teaching method at the Simav medical simulation center in Genova. The software that I will be using is SOFA Framework, while the hardware is the Geomagic Touch (previously called Phantom Omni).

In particular, this literature review focuses on some of the tasks that can be performed on the skin: needle insertion, suturing, incision and palpation. An important goal of this paper is also to study which of these tasks better exploit my available instruments.

The core of the study is in the next chapter, which is divided into two sections. Section A covers the state of the art of the skin and tool models. Section B is instead dedicated to the study of the medical tasks that are more often reproduced in simulation.

II. State of the art

A. Skin and tools models

1) The 3D models: In order to perform any kind of simulation relative to the skin, the physical model of the tissue and of the tools must be developed. This means 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.

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

Both methods are based on the discretization of the domain into sub-regions called elements, but in MSS a particle mass is also assigned to each vertex of the element and a spring and damper are set along each edge to connect the mass particles.

In 2003, LeDuc et Al. ([1]) 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.

In 2010, Payandeh and Shi ([2]) also use a mass spring approach and a simple iterative explicit Euler method to update states of soft tissue.

In 2008, Comas et Al ([3]) implement a CUDA-based nonlinear FEM into the SOFA framework. In particular, they impose the non linearity by choosing an anisotropic visco-hyperelastic model. They are able to speed up the overall process by moving most computations to the GPU.

In addition to discretization, it is also interesting to study the way of representing the skin appearance in terms of skin layers reproduced. For example, in 2019 Jayasudha et Al. ([4]) implement three layers (epidermis, dermis, subcutaneous layer) while in 2014 Yang et Al. ([5]), followed in 2020 by Moreau et Al. ([6]), implement one layer only. In general, the number of layers varies with the kind of task that must be performed and on the force feedback precision needed.

Regarding the *needle*, multiple simple models can be found in literature.
For example, in 2010 Payandeh and Shi ([2]) use a curved needle (suturing needle) while, in the same year, Choi at Al. ([7]) use a straight model. In general, the main idea is to use a volume made of 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 ([7]).
A literature research was made for the *scalpel* too, but results were very similar to the ones of the needle so they are not reported here.

Some *thread* models were also analyzed.
In 2002, Lenoir et Al ([8]) represent the thread curve as splines, using Catmull-Rom splines for their interpolation property and uniform cubic BSpline for their better continuity.

LeDuc et Al. ([1]) 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 ([2]) model it as a sequence of mass points linked by springs and Choi at Al. [7] use a sequence of segments linked by spherical joints.

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 on the 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.

These volumes can have different shapes. Both spheres ([2], [9]) and boxes are very common ([10]) but the choice of the shape (as well as the number of volumes) strongly depends on the object itself.

B. The medical tasks

1) Needle insertion into soft tissues: Needle insertion can be divided into three different steps: pre-puncture, puncture, complete penetration. Each step produces different forces on the needle ([6], [11], [5]). These forces 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 $F(x) = a_1x + a_2x^2$ (in 2004 Okamura et Al. [11], in 2014 Yang et Al [5], in 2019 Jayasudha et Al [4]) that recreates a non linear effect. In the equation, x is the needle displacement, d1 is the maximum displacement before skin is cut, a1 and a2 are constants to be determined (in [5]: a1=0.0019, a2=0.0499 and in [12]: a1=0.0480,a2=0.0052, and a1=0.0020,a2=0.0023).

Choi et Al ([7]) 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 latter 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 ([6]):

- Cutting force: Yang et Al. ([5]) calculate this force by measuring the total force at this phase and substracting the frictional force.
- Friction force: in 2011 Asadian et Al. [13] 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 papers ([14],[11]).
- Clamping force: this force is used in 2007 by Kikuuwe at Al. [15] and their model is adopted in 2020 by Moreau et A.l. ([6]). 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. ([7]). 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 ([16]). This method consists in 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 [5].

2) Hernia palpation: There are few papers about this medical task performed with the Geomagic device. This is because palpation would need a different force feedback on each finger, and the device only allows one point of feedback. An example I found is in 2012 from Ullrich and Kuhlen ([17]), who adapt the haptic devices with pads to provide real sensations. They perform dragging of the tissue and study the forces that are generated by using a bimanual station of Geomagic Touch.

3) Incision: This kind of simulation needs a scalpel and a skin patch, and the skin can be represented 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. A difficulty when simulating incision is that users expect to see the result of cutting as they move the instrument, without noticeable delay, and thus re-meshing must be performed as the cutting tool travels along its path. Here are reported some examples of incision found in the literature.

In 2004 Zhang et Al. ([18]) create a MSS of the skin with tetrahedral surface mesh and additional meshes built in run-time to simulate depth. They implement different methods for cutting: pierce-in, slide-in: cut-into, cut-through. After cut through has ended, two different primitives of the skin are defined.

In 2010 Zerbato et al ([19]) create a MSS of the skin that is based on matrix that stores positions, force and mass (update lasts 3ms). Calculations over this matrix are performed on the GPU. In particular, when cutting is done, they simply disable the spring contribution in that position.

In the same year, Gutierrez et al ([20]) create two different models (then superimposed on each other) by doing a XFEM / FEM model remapping. When collision between the scalpel and the skin is detected , they check for the next 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, therefore it exploits the 6 dof of the Geomagic Touch device and is 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.

In 2003, LeDuc et Al ([1]) 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.

In 2010. Payandeh and Shi ([2]) model the suture as a MSS that consists of a sequence of mass points laying on the centerline of the suture and connected together by various types of springs. The skin moves with suture if friction with suture is greater than spring force on node. Otherwise, it slides along it. They also add an example of unwanted event such as the ripping of the tissue, to make the simulation more realistic. Moreover, they use a bimanual station of Geomagic Touch.

In 2010 Choi et Al ([7]) model the interaction needle-skin as described in the needle insertion chapter. They use a bimanual station of Geomagic Touch.

Finally, in 2020 Sung et Al ([21]) 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 analyzing the state of the art of these medical tasks simulations and whether they can be performed with the Geomagic device, I restricted my options to Suture and Incision only.

The reason for excluding the Needle insertion option is because with the Geomagic Touch device it is hard to actually perceive the different kinds of forces relative to the skin layers.

I also rejected the Hernia palpation option 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 by using two devices with 3D printed pads and a support for fingers, but it would still be difficult to correctly perceive the tissue.

On the other hand, both incision and suture exploit the potentialities of the Geomagic, since they need 6dof to move in the space. These are therefore the two tasks that I will try to implement in my thesis.

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