Toward a Realistic Simulation of Organ Dissection

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Abstract. Whilst laparoscopic surgical simulators are becoming increasingly realistic they can not, as yet, fully replicate the experience of live surgery. In particular tissue dissection in one task that is particularly challenging to replicate. Limitation of current attempts to simulate tissue dissection include: poor visual rendering; over simplification of the task and; unrealistic tissue properties. In an effort to generate a more realistic model of tissue dissection in laparoscopic surgery we propose a novel method based on task analysis. Initially we have chosen to model only the basic geometrics of this task rather than a whole laparoscopic procedure. Preliminary work has led to the development of a real time simulator performing organ dissection with a haptic thread at 1000Hz. A virtual cutting tool, manipulated through a haptic device, in combination with 1D and 2D soft-tissue models accurately replicate the process of laparoscopic tissue dissection.

**Keywords.** Dissection, Cutting simulation, Task analysis

Introduction

Surgical procedures using laparoscopic and robot-assisted laparoscopic techniques use specialized instruments and cameras to perform surgical procedures through small (typically 1-2cm) skin incisions. By limiting the extent of surgical trauma in this way in is intended that patient recovery is improved. Unlike conventional open surgery laparoscopic techniques are often technically more demanding for the surgeon. As such major efforts have been made to create high fidelity computer simulations to aid surgeon training.

A major part of any surgical procedure is the separation of tissue through careful dissection. This process is often time consuming and requiring of considerable operator skill. The challenges of accurate tissue dissection are increased in laparoscopic surgery due to fulcrum affect experience when using long instruments pivoted on a body cavity wall, diminished haptic feedback and loss of eye-hand-target axis

This particular surgical task is one that is particularly difficult to model as such current computer based simulators do not meet the requirements for advanced surgical training.

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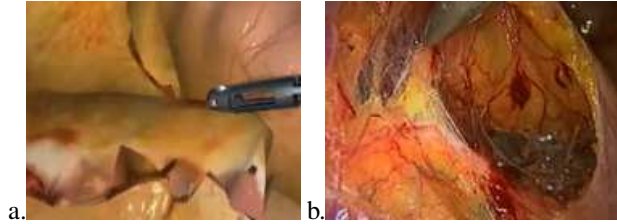
Figure 1. Fat tissue and peritoneum: (a) commercial simulator. (b) human patient

We propose here a new framework to simulate the tissue dissection task that has benefited from close collaboration between computer scientists and surgeons. The proposed model includes a 3D geometric framework that handles and can be dissected in the same way as in vivo tissues. This article outlines the design strategy and methodology for creating such a simulation as well as the initial results from its testing.

1. Methods & Materials

1.1. State of the art analysis

Tissue dissection in laparoscopic procedures is present in various commercial simulators like the LAP Mentor by Simbionix® and the MIST-VR by Mentice®. However, there remain some drawbacks concerning the organ dissection that alter the simulations realism, including: the interpenetration between the thin peritoneum (membranous lining of the abdominal cavity and organs within) and fat tissues; the triangle edges that give a too regular geometry (see Figure 1.a); the rendering of peritoneum and fat tissues as a continuous as opposed to a heterogeneous surface (see Figure 1.b); the automatic disappearance of fat tissue after being incised, and; the non physiological properties of fat tissues such that they can be excessively stretched without tearing or bleeding. The most significant limitation of existing simulators is that the dissection task is often too easy and too fast compared to a reality.

1.2. Task analysis

Dissection could be done with different kinds of tools [1]: standard scissors that cut but do not perform haemostasis; monopolar electrosurgery for coagulation often associated with a hook used to incise; thermofusion devices such as Ligasure® that cauterizes and cuts tissues, and; ultrasonic devices such as Harmonic Scalpel®. We chose to model the latter in our framework (See Figure 2). The procedural steps within this task that have been assessed by surgical experts are presented in Table 1.

### 1.3. Peritoneal structure

Fat tissues are often represented as a continuous medium with a uniform behavior. For example, in one study [2] fat tissue is modeled by a mass-spring system, the geometry of which is computed from a Marching Cube algorithm base on data from real patients. The realism of this model is poor as previously explained.

Table 1. Procedure task analysis: essential information of each step is described by subject matter expert to guide the simulator design

Steps of the task:

[1].	Ensure optimum quality of video image. Factors to consider include: illumination; focus; colour balance; horizontal axis, and; adequacy of field of view
[2].	Grasp tissues/organ from which fat tissues are to be dissected. If needed, separate two peritonea in contact
[3].	Identify intended plane of dissection
[4].	Ensure appropriate opposition of tissues such that force is applied perpendicular to the intended plane of dissection
[5].	Initiate dissection: • Approach intended plane of dissection with the Harmonic scalpel • Slightly pull upward tissues to dissect • Ensure haemostasis. It requires the tool diathermy activation. Tissues may slightly be attired by the tool • Tissues are slightly compressed • Use dissecting vibrating scissors to divide tissues in the intended plane of dissection • As dissection continues maintain appropriate tension across plane of dissection
[6].	Ensure that the tips of all are within the field of view at all times. Open, sharp tipped and diathermy instrument have the potential to cause damage to surrounding structures and tissues.
[7].	Use of diathermy with lead to the production of smoke that can limit the surgeons view. Under such circumstances, dissection should be temporarily halted until smoke clears or can be evacuated.

We chose instead to model the peritoneum as a heterogeneous structure composed of 1D and 2D models. The material is represented either by a surface within which there are holes or a set of lines constituting a web-like structure.

The 2D structure is in the form of an irregular grid, every point in which may be randomly moved in any direction. Spaces have been removed in the grid to create holes. The Catmull-Clark algorithm is then applied to soften the angles. In comparison the 1D structure comprises of a set of lines composed of several points that are moved, predominantly in the orientation of the tissue plane but also slightly orthogonal to the plane. Skinning is then applied to these lines to increase their thickness.
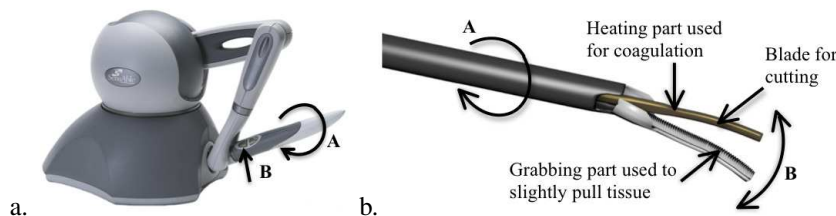
Figure 2. Surgical tool simulation: (a) Phantom Omni haptic device; (b) 3D surgical tool avatar linked to the haptic device with rotation A depending of the stylus orientation and scissor closure B linked to the button.
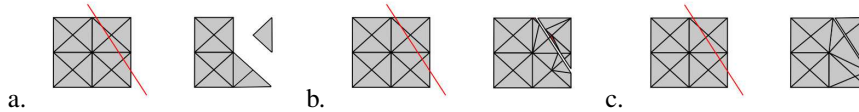
Figure 3. Cutting method: (a) Element removing, (b) Element subdivision, and ;(c) vertice displacement and separation

1.4. Soft-tissue deformation

A comparison of different soft tissue models has been conducted by the authors of a previous study [3]. They concluded that the application of these models is often a compromise based on specific needs.

In the case of this study tissue structures are modeled by mass-spring elements because it is fast enough to handle haptic rendering but also accurate enough to have a realistic behavior. Spring stiffness and damping may also be later tuned to simulate inter patient variability.

1.5. Cutting simulation

A 1D-cutting simulation is performed on the 1D elements of a web-like structure by subdividing the edge touch by the surgical tool into two spring elements. In order to follow the task analysis an initial axial traction is applied to the two new elements during 1s. The two element parts then follow gravitational and spring like retraction. This is achieved by setting the spring initial length to a value slightly inferior to the edge dimension.

2D cutting simulation is still an open problem but current models are becoming more realistic [4]. There are currently three solutions to simulate this procedure. (1) Removing the elements along the cutting path (Figure 3.a). This is very simple to implement and very fast, however, this algorithm gives unrealistic results. It requires a very fine mesh and leads to unconvincing results. In addition, it creates mesh singularities [5]. (2) Subdividing the mesh elements (Figure 3.b). The method consists of breaking down the components in contact with the cutting tool into several basic elements with the edges corresponding to the newly created cutting paths. Although realistic, this method is computationally heavy, due to the fact that whist the soft tissue surface is preserved, the node number dramatically increases, which increases the computation time. Another disadvantage of this method is that it can build degenerate triangles (surface to almost zero), which can lead to unstable behavior. (3) Initial displacement of vertices and separation method (Figure 3.c). This method, used by Nienhuys and van der Stappen [6], consists in first moving the closest point to the cutting path in order to separate the elements. As with the subdivision method, this technique has a high level of realism since cutting coincides exactly with the path of the cutting tool. It has the advantage of keeping the size of the mesh and thus allows the simulation to proceed at constant performance. However, it suffers from the same limitation of the creation of degenerate elements, necessitating triangle removal. Ultimately this third technique was adopted in the current simulation in combination with the algorithm developed by Botsch and Kobbelt [7], to suppress degenerated elements. As previously stated the behavior during and after cutting is simulating the real behavior described by the task analysis with the initial traction and the elastic recoil.

2. Results

The framework has been implemented in C++ using SOFA framework [8] for the organ deformation and for the topology changes. OpenHaptics was also used for the haptic rendering. The interaction with the virtual environment is performed using a Phantom Omni by Sensable®. Figure 2 shows the link between the device (Figure 2.a) and its avatar (Figure 2.b) as well as the features of the surgical tool. Its 3D geometry has been modeled using Blender®.

The geometry strategy is intentionally simple in order to focus on the task. The haptic interaction has a acceptable frame rate of 1000 Hz. In order to guaranty no discontinuity with the haptic feedback while cutting, the device is blocked. It simulates the 2-3 seconds needed for the cauterization.

Various steps of the task analysis are simulated: the initial traction along the axis; the time needed for cauterization, and; the natural elastic behavior of tissues following incision. The matter compression is however not yet implemented and the 3D rendering is not optimal.

3. Conclusions & Discussion

We have presented a framework for organ dissection. It is based on a close collaboration with surgical experts in order to focus on the realism. Novel outcomes of this work include: (1) a task analysis for organ dissection; (2) a new framework for organ dissection with haptic rendering and soft-tissue deformation, and; (3) an original fat tissue geometry design. The dissection process is based on existing cutting models from the literature with extra heuristic behaviors added in order to reproduce the physiological tissue properties. Early result consists of a basic 3D geometry that can be dissected with a tool following an original cutting simulation process.

Future work will include: improvement of the quality of the 3D rendering; investigation of the influence of different patient's parameters (quantity, elasticity, adherence, etc.). Finally, the model itself will be validated as a clinical tool.

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