Fatty Tissue in a Haptic Illustration Environment

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Abstract. Modeling soft tissue for surgery simulation is a challenging task due to the complex way that the tissue can deform and interact with virtual surgical tools manipulated by user. One soft tissue that is ubiquitous but often not modeled, is fatty tissue. Here we present a novel fatty tissue model based on the mass-spring system on the Graphics Processing Unit (GPU) as part of our Toolkit for Illustration of Procedures in Surgery (TIPS). The user can interact with the fatty tissue in real time via a handheld haptic stylus that represents a virtual surgical tool in TIPS environment. The currently available interactions are palpation, grasp, and cut.

Keywords. TIPS, Deformable object, Mass-spring system, GPGPU, Marching cubes

Introduction

The TIPS environment [1] (Toolkit for Illustration of Procedures in Surgery) places at an author's disposition: 3D anatomy representation, tool motion, force feedback via a handheld haptic stylus and various media such as images and texts. The goal is to enable a specialist surgeon to easily create a haptic interactive document that allows him/her to communicate specific 3-dimensional conditions, pathologies, procedures, anomalies and anatomical relationships — both realistically or overstated for education or publication. The resulting interactive, hands-on illustration allows – at any point – to pause, explore and repeat a component until the procedure is understood. A key issue in surgical procedures is the exploration phase preceding the actual clamping, cutting or other inter-

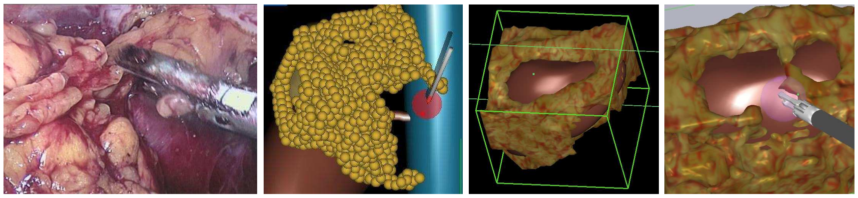

Figure 1. Fatty tissue. (a) dissection of real tissue during laparoscopic adrenalectomy. (b) old particle system, (c) instantiation of new volumetric representation, (d) interactive dissection.

vention. Figure 1a shows a screen shot of real fatty tissue during laparoscopy where a surgeon needs to verify the layout of smaller organs and vessels embedded and obscured by fatty tissue. In TIPS, fatty tissue is added in the Anatomic Layout stage – after the author populates the virtual 3D scene with predefined 3D models (organs, vessels, surgical tools) from an extendable database. Since models and their layout are interactively adjusted, fatty tissue has to be generated to adapt to the layout. The key challenge of such adaptive and deformable structures is to provide a consistent model
(i) for collision testing (tool–tissue, tissue–tissue, tissue–organ, etc.)
(ii) of physical feedback (resistance and force propagation) and
(iii) of visual representation.

The initial, proof-of-concept version of TIPS used a particle system to model fatty tissue (Figure 1b). Representing each fat nodule as a 'particle', an entity with position, radius and velocity, provides a quick solution to the challenges (i–iii). However, the particles lack the proper coherence and memory. Similar to billiard balls on a pool table, minute changes in the tool path can lead to a different particle distributions. This creates a problem for the replay of the dissection since the trajectory of each particle would have to be recorded.

We therefore replaced the particle system of fatty tissue by a volumetric deformable grid-structure. Collision testing (i) is based on bounding spheres, the physical model (ii) on a standard adjustable mass-spring system, and the visualization (iii) on a modified marching cubes algorithm. An author *initializes* the fatty tissue simply by placing a size-adjustable cube filled with volumetric fatty tissue into the scene (Fig. 1c). Excess material is removed by removal of the 3D nodes and their connections where the virtual device touches the fatty tissue. Initial cube coordinates serve as 3D texture coordinates for the boundary surface. With the initial texture coordinates under deformation, the surface appears to stretch naturally when the tissue is pulled. And the cutting simply creates a new, immediately textured triangulation. To preserve real-time manipulation, we ported the volumetric representations and computations to the Graphics Processing Unit (GPU).

Modeling Fatty Tissue

Our fatty tissue model consists of three closely coupled representations for *dynamic response*, *collision detection*, and *visualization*. All three representations are implemented on the GPU, rather than on the CPU, to leverage parallelism for speed. The dynamic response is a mass-spring system embedded in a 3D regular grid. The collision detection is based on bounding spheres. The visualization is a marching cubes algorithm modified for visualizing cuts in the model.

[Dynamic Response] The dynamic response is based on a 3D mass-spring system. This module responds to internal forces and external forces from the simulation environment, such as a gravitational force. The GPU computes the next position of each mass point of the system by using Verlet integration [2].

[Collision Detection] Each mass point in the system is bounded by a sphere and the virtual surgical tool is also approximated by a sphere and a cylinder for its tip and shaft, respectively. The GPU computes, in parallel, the intersection of the bounding sphere of each mass point with a virtual surgical tool. If the bounding sphere of the mass point intersects the bounding geometries of the tool, an offset is computed and added to the

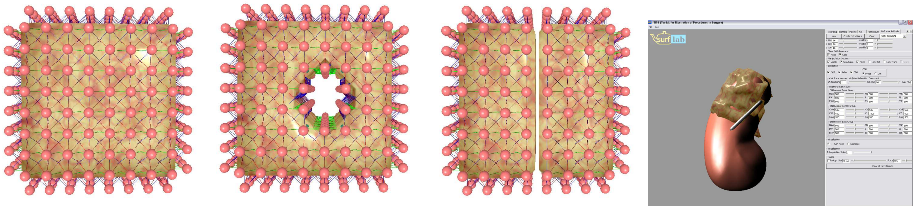

Figure 2. Fatty tissue. (a) the 3D regular grid and surface of fatty tissue. (b) after removing elements (or mass points), (c) after removing connections (or springs), (d) fatty tissue on the kidney covering the adrenal gland.

position of the mass point to move it away from the virtual tool. The offset is saved into the GPU memory. The offset is later retrieved by the CPU for computing the force feedback to the user via the handheld haptic stylus. The user can move the stylus to manipulate the virtual tool to change the shape of the fatty tissue in two ways; cauterizing (removal of 3D nodes, see Figure 2b) or cutting (removal of connections, see Figure 2c).

[Visualization] A marching cubes algorithm [3] is used to render the fatty tissue. The rendering is modified so that two surface pieces are generated, rather than just one, when connections have been removed from the spring system. (Figure 2c).

Application

Realistic fatty tissue is critical to our showcase application, *laparoscopic adrenalectomy* where fatty tissue has to be safely dissected to expose the adrenal vein in preparation for ligation in a variable layout of organs, vessels and fatty tissue. The unified representation of the collision, physical and visual model improves the realism and the reproduceability of the illustration sequence. The use of graphics hardware allows real-time interaction and authoring.

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