A Haptic Surgical Simulator for the Continuous Curvilinear Capsulorhexis Procedure During Cataract Surgery

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Abstract. This paper describes a technique for simulating the capsulorhexis procedure during cataract surgery. The continuous curvilinear capsulorhexis technique can be a difficult procedure for beginning ophthalmology surgeons. In the initial phase of tearing the tissue, the tear vector is tangential to the circumference of the tear circle. However, without the proper re-grasping of the flap of torn tissue close to the tear point, the tear vector angle quickly runs downhill possibly causing severe damage to the tissue. Novice surgeons tend to try to complete the capsulorhexis without the time consuming re-grasping of the tissue flap. Other factors such as anterior bowing of the lens diaphragm, patient age, and shallow anterior chambers add to the problematic nature of the procedure. Our capsulorhexis simulator models these various tear problems and anomalies to provide a training environment without the dangers of using live patients.

1. Introduction

Eye surgery necessitates sub-millimeter precision and demanding hand-eye coordination in a very small workspace, thus making it difficult to simulate. Some researchers have developed eye surgical simulators [1,2], but none have attempted to model the capsulorhexis procedure during cataract surgery. Our capsulorhexis simulator uses complex 3D graphical models, a high fidelity haptics force feedback device, and a mathematical model of various tissue tear problems to provide a training environment without danger to patients.

The continuous curvilinear capsulorhexis technique, developed by Gimbel and Neuhann, has become the standard method of anterior capsulectomy for phacoemulsification [3]. The capsulorhexis procedure begins by making a small incision with a cystotome in the center of the lens and generating a radial flap of tissue to grasp. The surgeon grasps the folded over flap of tissue and begins to tear in a circular motion such that the tear force vector is tangential to the circumference of the tear circle [4]. Angled forceps are used to grasp and pull the tissue circumferentially. All too often, beginning surgeons attempt to complete the capsulorhexis procedure without the proper re-grasping of the flap of torn tissue close to the tear point. This error in technique can cause the tear to run peripherally. If the surgeon attempts to redirect it by traction directed in a radial fashion toward the center of the lens, the tear only propagates further peripherally. It may even extend to the posterior capsule resulting in the complication of vitreous loss and/or the dropping of lens material into the posterior segment of the eye, necessitating more extensive corrective surgery. Anterior bowing of the lens diaphragm as well as a shallow anterior chamber can accentuate this peripherally directed tear phenomenon [5].
2. Methods and Tools

Our simulator uses the Sensable Technologies Phantom desktop device as the haptics force feedback unit (see Figure 1). The training software runs on a conventional Windows XP™ workstation with a 1.0 GHz Pentium™ processor (or higher) and an OpenGL™ graphics accelerator such as the Nvidia Geforce™ board. The training software has a data collection module that collects various metrics such as: time spent on the capsulorhexis procedure, tissue tear metrics, re-grasping time, and severe tear errors. Another software module records the motions of the user, which are used to replay the technique, thus showing the resident or mentor what the user did during the training session.

![Figure 1. (left) Phantom™ haptics force feedback device (right) Virtual instrument tearing the tissue.](image)

The tissue area is modeled as a curvilinear mesh of nodes and springs. Deformation is accomplished via our physically based particle model utilizing the mass-springs-damper connectivity with our modified implicit predictor to speed up calculations during each time step. Each vertex in the tissue mesh geometry has a mass and is connected to neighboring vertices with springs and dampers. The solution involves repeated application of Newton's 2nd Law of motion: $F = ma$ using an implicit solver for numerically solving the differential equations. The dynamics equation for each mass point is: $m_i \mathbf{x}_i = -\gamma_i \mathbf{x}_i + \sum g_{ij} + f_i$ Where: $m_i$ is the mass at point $\mathbf{x}_i \in \mathbb{R}^3$, $\gamma_i \mathbf{x}_i$ is the damping force to prevent instabilities, $g_{ij}$ is the linear Hookian force exerted on mass $i$ by the spring between $i$ and $j$, $f_i$ is the sum of the external forces acting on mass $i$ (gravity, pushing, pulling, and tearing the tissue). Combining the vectors of all mass points produces: $M \mathbf{x} + D \mathbf{v} + K \mathbf{x} = \mathbf{f}$, where $M$ is the mass matrix, $D$ is the damping matrix, $K$ is the stiffness matrix, and $\mathbf{f}$ is the aggregate force vector. As the system progresses through time $dt$, the first order differential equations are: $\mathbf{v} = M^{-1} (-D \mathbf{v} - K \mathbf{x} + \mathbf{f})$, $\mathbf{x} = \mathbf{v}$, where $\mathbf{v}$ is the velocity vector. To get around the computational expense of solving a linear system at each time step, we incorporate an approximate solver, that pre computes the solution to a linear system [6]. In addition, we are currently incorporating a heuristic algorithm to constrain the deformation calculations to the locality of the tear area to speed up the computations.

3. Results

The user begins the simulation by making a small incision in the center of the lens generating a flap of tissue to grasp. The user then grasps the flap and pulls the tissue towards the 12 o’clock
position using angled forceps. The software alerts the user of any potential tear problems before they occur thus instructing the novice surgeon. For example, as the user approaches the 12 o’clock position the tear vector *unintuitively* begins to run peripherally. If the surgeon attempts to redirect it by traction directed in a radial fashion toward the center of the lens, the tear only propagates further peripherally (runs downhill). Continuing to try to redirect the tear can cause severe damage to the tissue in an actual patient. Our simulator alerts the user to these and other problems (ex. when to re-grasp) to provide training in this procedure. Our training system provides a useful tool for beginning ophthalmology surgeons to experiment and test their skills before interaction with actual patients. Experimental use (beta testing) is currently underway. Clinical trials are expected to begin in December 2003.

![Figure 2. (left) Modified mass-springs model used for tearing the membrane (right) Side view.](image)

### Acknowledgments

This project is funded, in part, by the National Science Foundation under grant number EIA-0116616, the Neimeyer-Hodgson Grants Program, the Havemeier-Gibson Endowment for Computer Science, and by the Penn State University College of Medicine Department of Ophthalmology.

### References/Literature


