

# Simulating the Continuous Curvilinear Capsulorhexis Procedure During Cataract Surgery on the EYESI™ System

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**Abstract.** This paper describes a technique for simulating the capsulorhexis procedure during cataract surgery on the EYESI™ system. 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. The tissue area is modeled as a curvilinear mesh of nodes and springs. Deformation is accomplished via a physically based particle model utilizing a heuristic algorithm to constrain the deformation calculations to the locality of the tear area to speed up computations. The training software alerts the user of any potential tear problems before they occur thus instructing the novice surgeon. The EYESI™ hardware system (from VRMagic GmbH) provides the user with stereoscopic images thus providing 3D viewing. Our capsulorhexis simulator software models a number of tear problems and anomalies to provide a useful 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 eye simulator hardware platform, 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 [5,6].

## 2. Methods and Tools

There are basically three major paradigms for modeling soft tissue in surgical simulation: Finite Element Models (FEMs), mass-springs models, and hybrid approaches [7,8]. Although many researchers have used mass-spring models successfully to model cloth animations, VR facial expressions, and abdominal organs, there appears to be a movement afoot to use more hybrid models and algorithms to avoid issues of numerical instability and prohibitive computational complexity. We use a modified hybrid mass-springs system to take advantage of the computational speed and simplicity.

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. The dynamics equation for each mass point is:  $m_i \ddot{x}_i = -\gamma_i \dot{x}_i + \sum g_{ij} + f_i$  Where:  $m_i$  is the mass at point  $x_i \in \mathbb{R}^3$ ,  $-\gamma_i \dot{x}_i$  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:  $M\ddot{x} + D\dot{x} + Kx = f$ , where  $M$  is the mass matrix,  $D$  is the damping matrix,  $K$  is the stiffness matrix, and  $f$  is the aggregate force vector. As the system progresses through time  $dt$ , the first order differential equations are:  $\dot{v} = M^{-1} (-Dv - Kx + f)$ ,  $\dot{x} = v$ , where  $v$  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 [9]. In addition, we incorporate a heuristic algorithm to constrain the deformation calculations to the locality of the tear area to speed up the computations. As the mesh is pulled, a heuristic routine determines the direction of the tear based on the force vectors acting on the mesh. The parameters of this routine can be adjusted to model various capsule characteristics.

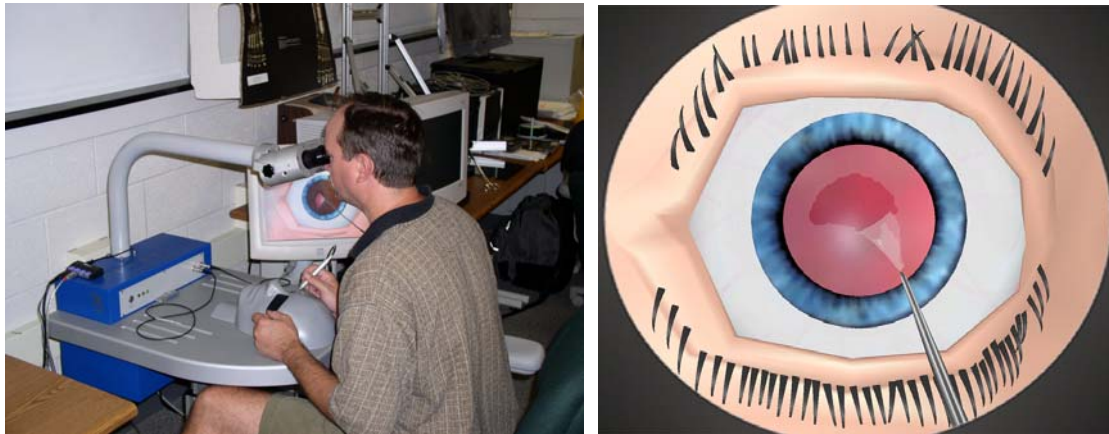


Figure 1. (left) The EYESI™ hardware system (right) Virtual instrument tearing the tissue.

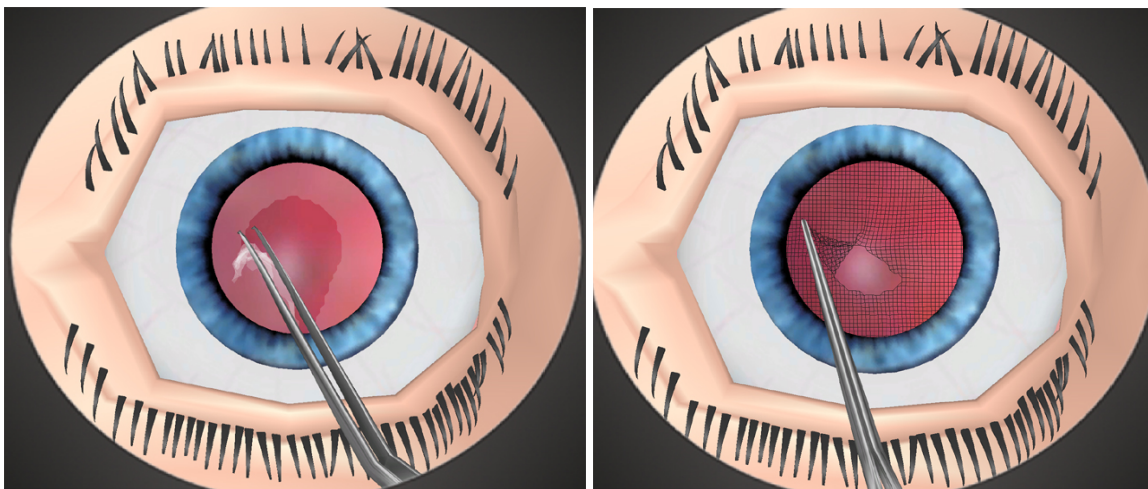


Figure 2. (left) The tissue after the tear has progressed too far radially (right) Modified hybrid mass-springs model used for tearing the membrane.

### 3. Results

Our training simulator software runs on the EYESI™ hardware system from VRMagic GmbH (see Figure 1). 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. Our training system provides a useful tool for beginning ophthalmology surgeons to experiment and test their skills before interaction with live patients.

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