SIMULATING 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 prototype capsulorhexis simulator models these various tear problems and anomalies to provide a training and learning environment without the dangers of using live patients.

KEY WORDS

Surgical simulator, capsulorhexis procedure, cataract surgery.

1. Introduction

Eye surgery is one of the most demanding micro-surgical tasks. The surgery necessitates sub-millimeter precision and demanding eye-hand coordination in a very small workspace. Some researchers have developed eye surgical simulators [1,2], but none have attempted to model the capsulorhexis procedure during cataract surgery. Our prototype 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 and learning environment utilizing simulation techniques instead of actual patients.

The continuous curvilinear capsulorhexis technique, developed by Gimbel and Neuhann, has become the standard method of anterior capsulorhexis for phacoemulsification [3]. The capsulorhexis procedure begins by making a small incision with a cystotome (bent needle) in the center of the lens and generating a flap of tissue to grasp. The surgeon then 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 towards the 12 o’clock position [5]. 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 can cause the tear to run downhill. In this case the tear will resist any attempt to redirect the tear uphill possibly causing severe damage to the tissue. As the novice surgeon continues to pull, the tear gets worse, no matter what the direction of the pull vector. In addition, anterior bowing of the lens diaphragm as well as shallow anterior chambers can accentuate this downhill tear phenomenon. In younger patients the tear may also follow the radial course of the zonule rather than the desired circular pattern [6].

2. Methods and Tools

Our prototype simulator uses the Sensable Technologies Phantom™ desktop device as the haptics force feedback unit (see Figure 1). The Sensable Technologies device operates at 1KHz so the user interaction with the 3D virtual instruments, virtual eye, and tissue model is essentially real-time. There is no perceived latency by the user when operating the simulator. 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 application software makes calls to our proprietary object oriented software toolkit called
MUOpenGL, which is an easy to use API (Application Programmers Interface) that calls OpenGL™ graphics routines. The toolkit provides additional functionality on top of OpenGL™ and has various objects and methods to rapid prototype simulation systems. The training software has a data collection object that collects various metrics such as: time spent on the capsulorhexis procedure, tissue tears, and severe tear errors. Another software object records the motions of the user. This is accomplished by recording the positions and orientations of all 3D graphics objects. Thus, the 3D graphics are used to replay the technique, showing the medical student or mentor what the user did during the training session.

The three dimensional (3D) models of the virtual angled forceps tool, the bent needle cystotome, and the eye were built in 3D Studio Max™ and are stored as 3ds files. The 3D model of the angled forceps and cystotome tools are loaded into the graphics simulation and react to the user’s manipulation of the Phantom haptics device handle (Figure 1). Pressing a button on the handle opens and closes the forceps.

![Figure 1. Sensable Technologies Phantom™ is used as the haptics force feedback device.]

4. Instrument – Tissue Interaction

There are basically three major paradigms for modeling soft tissue in surgical simulation: Finite Element Models (FEMs), mass-springs models, and hybrid approaches [7]. 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 mass-springs (hybrid) system to take advantage of the computational speed and simplicity [8]. The tissue area is basically modeled as a curvilinear mesh of nodes and springs (Figure 4). Mass is assigned to each vertex (node). Hookian springs connect neighboring nodes.

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 (Figure 5). This system consists of a set of point masses (nodes) connected to each other with a network of springs and dampers. Each vertex in the tissue mesh geometry has a mass and is connected to every other vertex 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.

As the novice surgeon continues to pull, the tear gets worse and is indifferent to the direction of the pull vector. Our simulator alerts the user to these and other problems to provide training in this procedure.
The dynamics equation for each mass point is:

\[ m_i \ddot{x}_i = -\gamma_i x_i + \sum g_{ij} + f_i \]

Where: \( m_i \) is the mass at point \( x_i \in \mathbb{R}^3 \),

\(-\gamma_i x_i\) 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, probing, pulling and tearing the tissue).

Combining the vectors of all mass points produces: \( M \dot{x} + D \dot{x} + Kx = f \), 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.

The fundamental problem with these implicit solvers is that they need to solve a linear system at each time step, which may not be practical with today's computers. To get around this computational expense, we incorporate a technique, based upon the work of Desbrun, et.al. [9], with an approximate solver that pre computes the solution to a linear system. In addition we have incorporated a heuristic algorithm to constrain the deformation calculations to the locality of the tear area to speed up the mass-spring computation.

5. Conclusion

This paper has described a system for simulating and training on the capsulorhexis procedure during cataract surgery. Instrument – tissue interaction and modeling of the soft tissue of the eye membrane has been delineated. Our training system provides a useful tool for beginning ophthalmology surgeons to experiment and test their skills before interaction with actual patients. Clinical trials are expected to begin in June 2004.

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7. References/Literature


