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A High Performance Graphic and Haptic Curvilinear Capsulorrhexis Simulation System

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Abstract—**A computer based curvilinear capsulorrhexis simulation system known as Virtual Phaco Trainer is presented. Interested residents and surgeons can use this system to navigate through the capsulorrhexis procedures and practice their skills. Performance data is presented after each practice with built in objective performance evaluation metrics. The system makes a number of important contributions A mass-spring model based anisotropic mesh is used to simulate a deformable capsule model along with a smooth curvilinear capsulorrhexis path. To navigate precisely, a Phantom haptic device is used to track positions as well as to provide snag-free haptic feedback. Solutions to conflicting requirements between a high density mesh update frequency and a high haptic feedback update frequency are addressed. Promising evaluation results from a group of ophthalmology residents and attending surgeons are presented and discussed.**

I. INTRODUCTION

In this paper, we present our efforts in designing a computer based capsulorrhexis simulation system known as Virtual Phaco Trainer. Ophthalmology residents and surgeons can use this system to navigate through the capsulorrhexis procedures to practice their skills. We adopt an anisotropic capsule model to simulate a smoother curvilinear path, a haptic device to provide tactile feedback, and the concept of "active node set" to address the conflicting requirements between the update frequency of a high density mesh and that of high haptic feedback. We also propose an objective performance evaluation mechanism to measure the performance of a training process. Preliminary evaluation and feedback are collected from a group of ophthalmology residents and attending surgeons.

In section II, we review previous research works on capsulorrhexis simulation. In section III, we present details of the design of the Virtual Phaco Trainer system. In Section IV we discuss its performance.

II. PREVIOUS RESEARCH WORKS

The EYESI simulator [2] [5] has two physical instruments inside a mechanical model of the eye. Positions of the instruments are tracked by three CCD cameras. One disadvantage is that the user feels a static mechanical model, which is not flexible for various cataract levels and different practice.

In the PhacoVision system [4] [6], the user has either a monitor or a microscope displaying the virtual microscopic image. A standard microscope pedal is available for control. After the training, feedbacks are presented to the user. One disadvantage is that, there is no haptic feedback provided to the user.

Agus et al [1] developed a virtual reality simulation system for cataract surgery training. Even though they employed a Phantom device as a 3D tracking device (to get position and orientation of the instruments), that system did not provide force feedback as the user touches the lens and the capsule. Therefore, that simulation was restricted to only visual feedback.

Doyle et. al. [8] presented a simulator with haptic feedback in 2008. Though the authors claimed that "the simulator is the first to feature haptic feedback in a cataract surgery procedure", Webster et. al. [7] have presented a haptic simulator on capsulorrhexis procedure in 2004. However, for both the systems, no performance details (such as the graphical rendering rates, the number of triangles in the mesh, the experimental results obtained, user feedbacks) are available for validation and further comparison.

A comparison of the EYESI simulator, PhacoVision system and our Virtual Phaco Trainer system is shown in Table 1. Details are explained in later sections.

III. VIRTUAL PHACO TRAINER SYSTEM DESIGN

A. System Architecture

Figure 1 shows an overview of the system architecture. The system consists of four key components: a graphic processing unit (GPU) for graphic rendering, a Phantom haptic device for haptic feedback, a Head Mounted Display (HMD) for stereo display, and a pre-built anisotropic membrane model for deformation.

B. Graphic Rendering Module

In the simulation system, we adopt virtual instruments (See "Instruments" in Table 1) for flexibility.

The position and orientation of the virtual instrument are tracked by the Phantom haptic device and then used to compute the current transformation and deformation. The graphic rendering module renders the scene accordingly onto the stereo display for user viewing.

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Table 1. Comparison of EYESI, PhacoVision and our Virtual Phaco Trainer system

	EYESI	PhacoVision	Virtual Phaco Trainer
Instruments	Two fixed real operative instruments	A nucleus manipulator and a phacoemulsification hand piece	Phantom device and flexible virtual instruments
Eye Model	A physical mechanical eye model	An M-base software working on top of Cosmo 3D/Optimizer	A virtual model based on anisotropic mesh
Deformation Algorithm	Mass-spring model	N/A	Mass-spring model
Tracking system	Three CCD cameras	Analog electronic transducers	Phantom device
Tracking rates	17 Hz	N/A	1000 Hz
Tracking accuracy	<0.1mm or 0.3mm	N/A	0.055mm
Graphical resolution and refresh rates	800x600,	1280x1024, 25Hz	800x600, 100Hz; 1024x768, 85Hz;
Graphical frame rates	12Hz for stereo, 25Hz for non-stereo	N/A	50-60 fps, stereo
Haptic Feedback	from the mechanical eye	No	from the virtual model

N/A (Not Available)

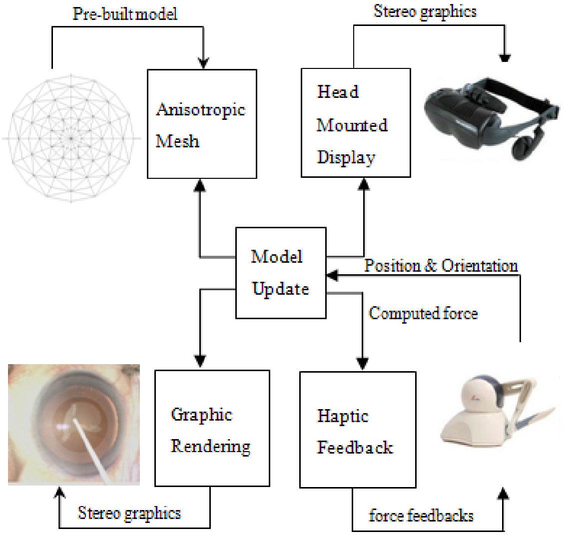


Fig 1. System architecture

In our simulation system, two graphical display modes are available: a HMD is used to provide a microscope-like environment similar to a real surgical microscope; and an external CRT monitor is used to display the same graphic scene for simultaneous viewing by multiple individuals. Figure 2 shows the two displays.

For the HMD, the refresh rate is set at 85Hz @ 1024x768, 100Hz @ 800x600 resolutions. For the CRT monitor, the refresh rate is 120Hz @ 1280x1024 resolutions (Refer to "Graphical resolution and refresh rates" in Table 1). Both provide flickering-free graphical rendering.

Fig 2. HMD (left) version and CRT monitor (right) version of the system

C. *Haptic Feedback Module*

The Phantom device in this module plays two roles. One role is to provide position and orientation tracking, up to an accuracy of 0.055mm (See "Tracking accuracy" in Table 1). The other role is to provide force feedback at a rate of 1000 Hz. Details of force computation are discussed in section E.

Unlike graphic rendering which needs 30 frames per second, haptic feedback needs a much higher 1000 Hz update. For a higher resolution model, the graphical rendering of the tearing path can be rendered more smoothly, but at the expense of slower system update, which results in unstable and unrealistic haptic feedback. To solve this problem, we introduce a concept of "active nodes set". Details of the active nodes set are discussed in Section D.

D. *Model Update Module*

We choose the mass spring model to implement the deformable membrane. In this model, the membrane consists of a mesh of particles with mass; each particle is connected to its neighbors via springs. A threshold is set for each particle according to its type, which, if exceeded, would cause the particle (and corresponding spring) to be either cut or torn.

For the topology of the model, we adopted an anisotropic model to for the membrane. In this model, each vertex has either 4 or 8 neighbors (except the center vertex, which may have more neighbors).Compared to the isotropic model, anisotropic model has the advantage that the tearing direction has smoother alternatives for expansion than an isotropic model.

Next, we discuss our simulation of the cutting and tearing. In [3], Lim and De introduce a concept of "region of influence" to simulate finer cutting. To model cutting on a high resolution model, we adopt a similar approach, but with improved updating performance. Instead of dynamically dividing the cutting triangles into smaller ones, the cutting works directly on a high resolution model to save the extra computation cost of triangular mesh division. With the introduction of “active nodes set”, this becomes possible.

With the high resolution model, we observe that spatial locality property is applicable to the simulation. That is, at any time, only a small portion of nodes close to the leading grabbed node are affected. Thus, instead of updating all the nodes in every update cycle, we keep track of and update only a small portion of the nodes, which we call active nodes set. An active nodes set is a set of neighboring nodes that are within k-hops to current node (See Figure 3 for an illustration of active node set). For example, in our simulation system, with $k = 5$, the active node set has a size of 120, which is only 6% of the total number of nodes (which is 2005) in the model.

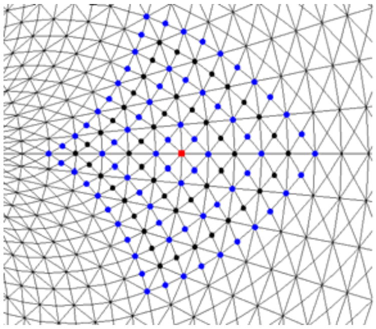


Fig 3. The blue and black nodes are the nodes consisting the active node set ($k = 5$) for the red node.

With the introduction of active node set, we greatly reduce the workload of the model update module, thus speeding up the update of a high density model.

E. Force computation

For node i with velocity v_i, we have forces as follow:

1. *Spring forces* follows Hook’s law.

$$f_{si} = -k_{sij} * dx_i,$$

where k_{sij} is the spring constant connecting node i and node j.

2. *Damping forces* tend to reduce oscillation effects.

$$f_{di} = -k_d * v_i$$

where k_d is the damping factor.

3. *Viscoelastic forces* are caused by the viscoelastic material injected.

$$f_{vi} = -k_v * v_i$$

where k_v is the viscoelastic factor.

4. *Overall forces* are obtained by summing up the above forces.

$$F_i = f_{si} + f_{di} + f_{vi}$$

The spring constant, the damping factor and the viscoelastic factor in above equations are fine tuned by experimental trial. In our implementation, $K_{sij} = 10.0$ or 40.0, depending on its type. The sum of K_d and K_v is 0.1.

5. *Feedback forces* are computed as proportional to the penetration depth into the lens.

$F_f = -k_f * d$ where k_f is the force constant and d is the penetration depth.

Though users should avoid touching the lens, the touching force feedback gives the user a cautious remind to be more careful and is mimic to lens touching in real surgery.

F. Results

The simulation system runs on a computer with dual Intel Xeon 3.60 GHz CPUs for model update, an nVidia Quadro FX 4500 GPU for graphic rendering, a SensAble PHANToM Omni system for haptic feedback and 6-DOF user input operations, an i-glasses PC HMD for stereo display.

The haptic workspaces of the simulator is adjusted to be placed right on the surface of the workstation; a circle on the surface of the workstation marks the position of the virtual eye; the height and orientation of the HMD can be easily adjusted to adapt to different user settings. With these measures, the user can easily get hand-eye coordination to operate on the virtual eye they see through the HMD.

In the system, we have a capsule model with 2005 vertices and 3944 triangles. The graphic rendering rates are about 60 fps with no tearing in progress, and 50 fps with tearing in progress. Haptic feedback is stable, no jerk or snag is perceived.

Figure 4 shows the capsule membrane during and after tearing.

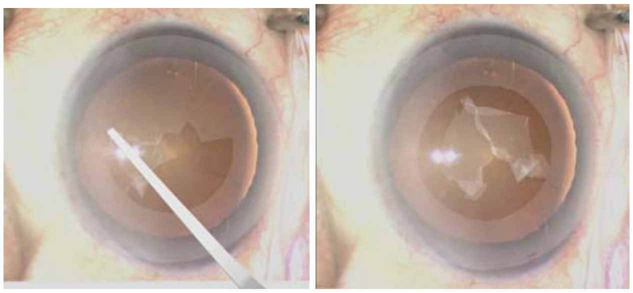


Fig 4. Screenshot of the capsule membrane during tearing (left) and after tearing (right).

IV. DISCUSSION AND CONCLUSIONS

A. Preliminary Evaluation and Feedback

A group of 15 ophthalmology residents and 3 attending surgeons from University of Illinois Medical Center were invited to use the Virtual Phaco Trainer simulation system. Anonymous questionnaires were handed out to collect feedback on the effectiveness of the system.

The results of the questionnaire (Figure 5) are encouraging. Most participants felt that simulation would be useful in improving their surgical skills. The mean and standard deviation of the responses from 18 participants are shown in the figure.

B. User Performance Evaluation

In the system, several objective parameters can be logged and analyzed for evaluation purpose, such as the total time taken to complete the capsulorrhexis procedure, the number of times that user re-grabs the anterior lens capsule, the number of lens hits by the forceps, etc. These parameters are chosen to reflect the different behaviors between experienced surgeons and residents. User performance analysis results based on these parameters are compared with a subjective review of on-screen video recording from the computer.

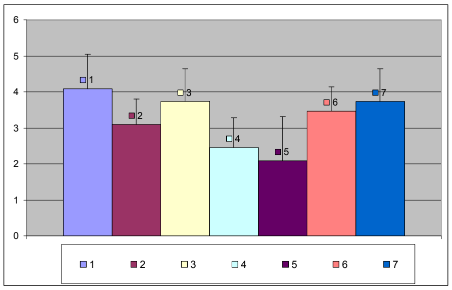
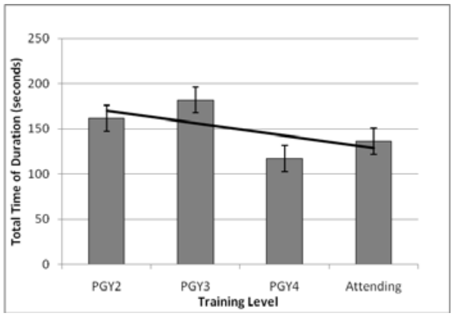
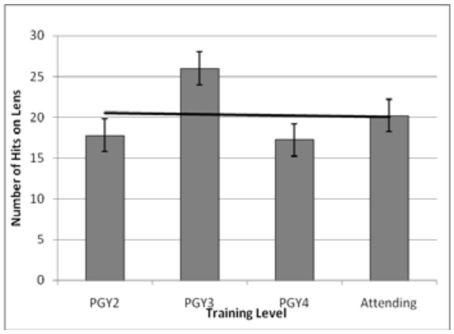


Fig 5. Bar graph showing user feedback mean scores (the bars) and Standard Deviations (the line segments on top of each bar) . Score Range: 1 (low) to 5 (high). Questions: 1. Do you think simulation is useful for developing surgical skills? 2. The experience is better compared to pig eyes. 3. Easy to use. 4. Closely mimics the OR experience. 5. Is a reasonable substitute for actual experience? 6. I think it will help improve my surgical skills. 7. I would use this in the future if available.

Figure 6 shows the performance data from this study with a trend line included. The users are divided into 4 groups: PGY2, PGY3, PGY4 and Attending, according to their post-graduate year.

Overall, the total time duration to perform the capsulorrhexis showed a trend where it appeared to decrease with the level of training, the number of hits on the lens was fairly uniform with a few outliers. Interestingly the grab-release of the capsular edge appeared to increase with the level of training. Evaluation of the video segments of the practice showed repeated careful handling of the edge of the capsular tear by experienced surgeons as the capsulorrhexis progressed, which partially explains the observation.





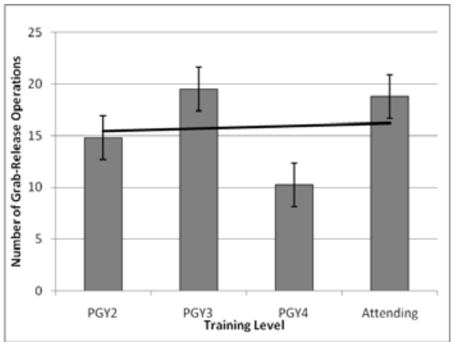


Fig 6. Training performance for (top) total time of duration, (middle) the number of lens hits, and (bottom) the number of re-grasp of the capsule membrane.

In summary we have developed a high performance graphic and haptic simulation systemfor training and the system may provide objective assessment of skills and competency.

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