Patient Specific Surgical Simulation System for Procedures in Colonoscopy

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Abstract

We have assembled a preliminary environment for simulating tasks that are performed in colonoscopy to provide a professional learning experience. Different commercial endoscopy simulators exist and provide realistic interfaces, but none of these products are able to simulate realistic soft tissue deformations using patient specific preoperative CT or MRI colon datasets. Colon models are represented as deformable objects within physically-based modeling simulation system. The simplified mass-spring system models an object as a collection of point masses connected by linear springs in a mesh structure. We can import patient specific high resolution meshes from MRI and CT abdominal examinations into a system that models objects with different physical properties for interaction with both non-force-feedback and haptic devices. The score tip of the colonoscope with instrument channel, irrigation, lens and light is modeled and the working channel allows interactions with different instruments as an endoscopic biopsy forceps and a snare (lasso tool) for polyp extraction. This virtual reality system for simulating virtual colonoscopy and polyp extraction can be used to simulate diverse procedures on a variety of pathologies in a novel physical environment and hopefully can shorten training periods and reduce complications.

1 Introduction

Colorectal cancer is the second leading cause of cancer-related death in the United States and in Europe [1]. But unlike many other forms of cancer (lung cancer, carcinoma of the breast, and so forth) the cause of this disease is clearly understood [2]. In the vast majority of colorectal cancers, an adenoma undergoes malignant degeneration. If benign adenomas are removed prior to the development of malignancy, colon cancer is essentially preventable [3]. To prove effective in reducing mortality from colorectal cancer, new screening methods must demonstrate a high diagnostic accuracy at a low cost, and prove safe and highly acceptable to patients. With the introduction of multidetector CT (MDCT) and advanced strategies for fast 3D MR imaging, the concept of virtual colonoscopy has become realistic. The CT colonography (CTC) and MR colonography (MRC) techniques are new radiologic techniques that promise to be highly sensitive colorectal screening examinations. Promoting colon polyp screening programs, even more polyps will be found and therefore more polyp extractions are requested. Colonoscopy and endoscopic interventions are already procedures for experienced professionals and for difficult tasks, years of experience is needed. Depending on individual skill, between 100-180 procedures, done over a 2-3 year period, are required before trainees can be considered competent in colonoscopy [4]. Highly realistic simulation of colonoscopy procedures is essential in providing a professional learning experience. To address this issue, we have assembled a preliminary environment for simulating tasks that are performed in colonoscopy. Different commercial prototype endoscopy simulators exist and provide realistic interfaces using the same hardware as used for conventional colonoscopy, but none of these products are able to simulate realistic soft tissue deformations using patient specific preoperative CT or MRI colon datasets. This paper presents a virtual environment for the simulation of colonoscopy procedures incorporating patient specific data providing an interactive, semi-immersive, haptic interface to the user.

2 Materials and Methods

A virtual-reality-based endoscopic polyp extraction simulator was produced. It involved the design, production and integration of:

- new data acquisition strategies for MD-CT and MRI colonoscopy
- patient specific 3-D colon and polyp models for preoperative planning and general simulation
- surgical simulation system employing soft-tissue modeling techniques
- specific endoscopic instruments
- specialized haptic interfaces
- advanced display devices

The development also included a user interface to allow the selection of various procedures and to present data concerning task completion times, forces exerted during procedures, etc.

Patient Preparation

The CT colonography and MR colonography techniques require proper patient preparation prior to scanning. This currently includes a bowel cleansing regimen, possible use of an oral contrast agent or bowel relaxant, and instillation of colonic contrast (air for CTC or dilute gadolinium solution for MRC). For bowel cleansing patients receive a standard oral colonoscopic bowel preparation the day before the examination (X-Prep ® (Mundipharma, Limburg, Germany) or oral Phosphosoda (CB Fleet, Lynchburg, Virginia), each with bisacodyl tablets (Dulcolax ®, Boehringer Ingelheim, Germany). The use of iodinated oral contrast to improve polyp detection in CTC is contested. Oral contrast theoretically increases the opacity of colonic fluid so that polyps surrounded by fluid can be identified. In this manner, oral iodinated contrast may reduce the number of false negatives due to excess colonic fluid. Some investigators routinely give 30 ml of oral iodinated contrast 1±2 h prior to scanning, and have found its routine use helpful. However, a recent study at the Mayo Clinic found that oral contrast did not improve the detection of colonic polyps in CTC, even in a subset of patients in whom the density of colonic fluid significantly increased. In the same study, when prone scanning was added to supine scanning, there were no false negative exams for polyps of 1 cm resulting from excess colonic fluid; thus, prone scanning may obviate the need for oral contrast by eliminating errors due to excess colonic fluid.

Multidetector CT Colonography

Multidetector CT provides the radiologist with unparalleled capabilities for detailed analysis of normal anatomy and pathology. Unlike classic single detector spiral CT where slice selection was determined prior to the study and was fixed, with MDCT there is more flexibility as with each individual detector bank a range of possible variable slice thickness can be obtained which can be selected even after the study is completed. MDCT provides potential true isotropic datasets, which may be important in the wide range of clinical applications ranging from 3D imaging to early detection of small colorectal polyps.

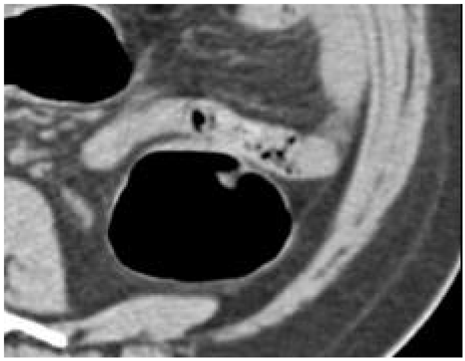

Figure 1. Pedunculated polyp on MDCT.

Virtual colonoscopic CT examinations are performed after a rectal tube is inserted, and the colon is gently insufflated with room air or carbon dioxide to the maximal level tolerated by the patient. A standard CT scout film of the abdomen and pelvis is acquired to assess the degree of colonic distention, and additional air is insufflated as required. Most CT examinations focused for virtual colonoscopy are performed according to standard abdominal protocols. Supine and prone images are obtained at most centers. Multidetector scanners can be used to acquire the entire data set in one 20-second breath hold. This rapid examination without the use of sedation and intervention is well tolerated and is assessed by patients to be more comfortable when compared with other full colonic examinations such as barium enema radiography or conventional colonoscopy. Patients appreciate that the inter-rogation of the colon is performed on the MDCT data at the physician's computer and not on them, which spares them time and discomfort. We suggest for MDCT a low dose virtual colonoscopy screening protocol and a high resolution protocol for focused virtual colonoscopy (staging cancer, known lesions).

MR-Colonography

For the MR-exam the patient is placed in a prone position onto the MRI table. A contrast enema is administered per rectum using a disposable enema kit with an inflatable tip by hydrostatic pressure (1-1.5 m water column). The enema consists of 2000 ml of water spiked with 20 ml of a 0.5 molar Gd-DTPA solution. To reduce bowel motion, scopolamine (20 mg) is administered iv as the patient was placed on the MR table. Imaging is performed on a 1.5 T MR scanner (Signa Echo Speed, GE, Milwaukee, Wi), equipped with ultrafast gradients. Filling of the colon is monitored with a 2D acquisition, one image per second.

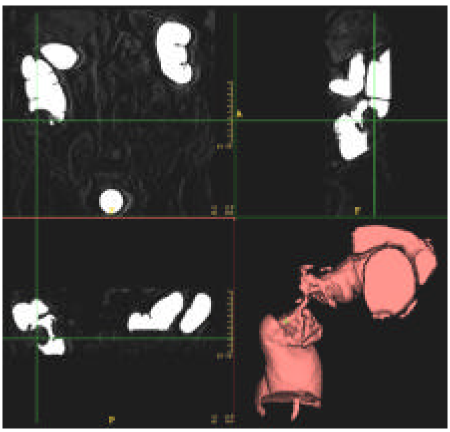

Figure 2. Rectal carcinoma on multiplanar MR images. The tumor stenosis is illustrated on the SSD image in the rectosigmoidal angle.

Once contrast has reached the cecum, a 3D Fourier transform gradient echo sequence with spoiling gradients is used to image the colon with 2 mm slice-thickness rendered a voxel resolution of 1.25 x 2 x 2 mm3. Within a 28 second breathhold 64 contiguous 2 mm sections are acquired. Subsequently the patient is imaged in the supine position. Due to lack of invasiveness and ionizing radiation in conjunction with satisfactory diagnostic accuracy MRC appears to have considerable potential to become a powerful method for colorectal cancer. However, several aspects of current technique of MRC require improvement before implementation as screening tool. CTC as well MRC still require a rigorous cleansed colon, thereby limiting patient acceptance. To obviate bowel cleansing before MRC examinations, the recent concept of fecal tagging was devised. Fecal tagging is based on oral ingestion of MR contrast agent that renders signal intensity of fecal material bright on 3D GRE images similar to that of the surrounding enema. The concept is feasible and eliminates the need of bowel cleansing prior to MRC [5].

Segmentation-3D Reconstruction

The segmentation was performed using Amira 2.2 (Template Graphics Software Inc., San Diego, CA). Amira provides 3D-image segmentation with several special-purpose features, ranging from purely manual to fully automatic. In our reconstruction process, we used the automatic thresholding function along with manual region selection functions to provide reasonable segmentation for extracting the bowel lumina. Once the organs of interest (i.e. colon, rectum) in a 3D-image volume have been segmented, a corresponding polygonal surface model is extracted using the Generalized Marching Cubes module. Resulting meshes of the colon consisted of over 1 million triangles. This meshes were then simplified using the mesh simplification module, resulting in mesh of under 100,000 polygons, which are more reasonable for interactive simulations.

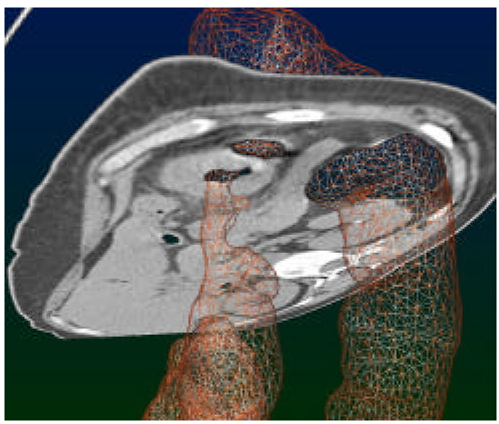

Figure 3 demonstrates the segmentation and mesh generation process.

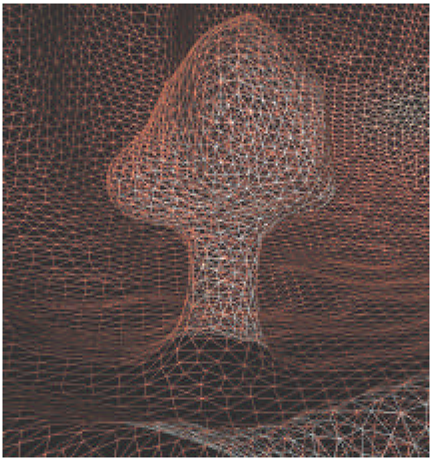

Figure 4 shows a close-up of the high-resolution mesh around the polyp.

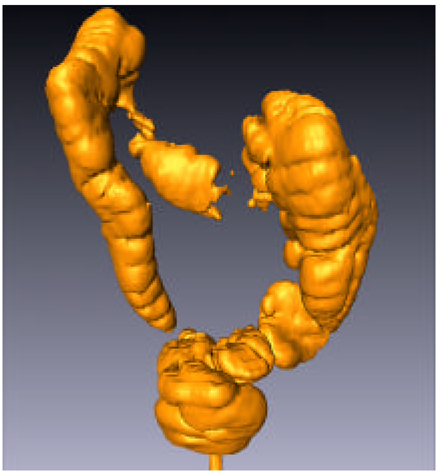

Figure 5 illustrates an entire high-resolution mesh of a colon with 2 carcinomas in the transv. part.

Virtual Endoscopy

After the computer model is generated, a simulated virtual endoscopy is performed. Virtual endoscopy (VE) describes a new method of diagnosis, using computer processing of 3D image data sets (such as from spiral CT, MDCT or MRI scans) to provide 3D visualizations of patient-specific organs similar or equivalent to those produced by standard endoscopic procedures. Conventional endoscopic examinations are invasive, often uncomfortable, and may cause serious side effects such as perforation, infection, and hemorrhage. VE avoids these risks and when used prior to a standard endoscopic exam may minimize procedural difficulties, thereby decreasing the morbidity rate. Additionally, VE allows for exploration of body regions that are inaccessible or incompatible with standard endoscopic procedures. When a camera is being led along a light source, the colonic surface cannot be seen completely, due to the limit of the angles and the inevitable blind spots. In order to get around this problem, the patients are being scanned both supine and prone in order to circumvent problems with fluid and with distension of the different segments. In addition, rotating the camera around 360 degrees covers the entire colonic mucosa. Endoscopists cannot see this full a picture.

Preoperative 3D images such as virtual endoscopy projections are helpful to confirm or improve the observers confidence that a lesion is present and to display complex bulbous folds, the ileocecal valve region or the inner contour of a flexure. In our system, common rendering options, such as coloring, lighting, solid/wire drawing and view control for virtual endoscopy are.

Simulation System

The core software for modeling the physics of soft tissue dynamics is the spring system developed by the National Biocomputation Center, and has been previously used for surgical planning and analysis, a microsurgery suturing simulator [6], diagnostic and operative hysteroscopy simulator [7] and an animal dissection trainer [8]. The visualization component of the system allows the user to view the mesh data in monoscopic or stereoscopic as wireframe, solid, or semitransparent objects. The software is written in C++ using the OpenGL, GLUT, and GLUI libraries and runs on many different computing platforms. For this project, the simulation ran on a Sun Ultra60 Elite3D graphics workstation with two 500 MHz UltraSPARC processors and 1GB of main memory. The software is multithreaded and dedicated one processor to graphics and the other to communication, collision detection, and simulation. The simulator also includes a shell user interface containing the instructor and student front-end for the simulator. The interface allows the student to view general or skill-specific instructions, as well as select various procedures including diagnostic endoscopy, endoscopic biopsy procedures and removal of polyps of various sizes.

Soft-Tissue Modeling

In order to provide real-time, haptic-compatible update rates of truly arbitrary deformations, a simplified mass-spring system is currently the only modeling paradigm capable of providing adequate performance. Although some researchers have described advances in the use of finite element models to model localized soft-tissue deformations [9], this simulation not only requires coupling regions with varying stiffness but also performs interactive mesh manipulation via cutting [10].

In the system, a soft tissue object is modeled as nodes (point masses) connected by edges (springs), which are grouped in triangles for the purpose of visualization. Forces are exerted on each node by the adjacent springs, by damping, by torsion between adjacent triangles, and by the surgical instruments controlled by the user. Known physical properties of tissue are used to provide appropriate values for these forces and ensure realistic simulation. Simple and fast iterative numerical methods (Euler, Runge-Kutta, or quasistatic) calculate each nodes position and velocity based on these forces, which can then be used to deform the object in real-time at haptic rates (>1000Hz). The system uses constraints to limit processing requirements to provide for increased scalability while maintaining adequate update rates. In order to speed up the simulation further, we have chosen to solve the deformation equations asynchronously, using a multithreaded model on multi-processor Sun UltraSparc workstation (Mountain View, CA).

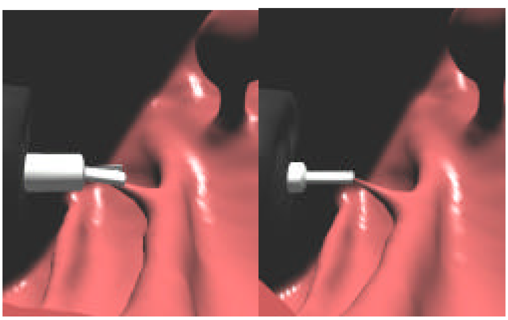

Figure 6: Performing a tissue sample using the endoscopic biopsy forceps (left). The forceps are closed while grabbing the deformed tissue (right).

Collision Detection

Real-time, haptic-rate collision detection [11] was performed by a modified hierarchical Bounding Spheres algorithm [12]. In order to decrease the search space of the Bounding Spheres tree a novel tagging technique was employed. Each leaf node in the tree (corresponding to a triangle) was marked with an enabled flag. For enabled leafs, the enabled value was proposated to parent nodes to effectively define the parts of the tree to be considered.

Instruments-Interactions

For probing and tissue extraction, a number of different endoscopic tools were developed and integrated using commercial CAD applications (3D Studio MAX, Kinetix). The score tip of the colonoscope with instrument channel, irrigation, lens and light is modeled and the working channel allows interactions with different instruments as an endoscopic biopsy forceps and a snare (lasso tool) for polyp extraction. The user can feel the force profile of grasping and cutting through both the polyp as well colon tumors.

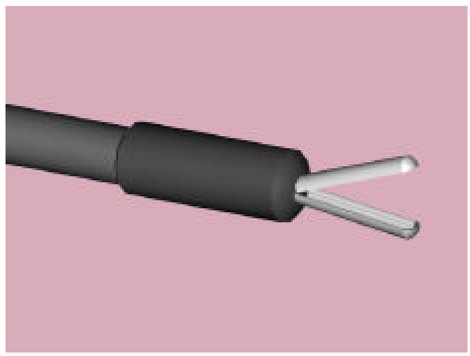

Figure 7 illustrates the tip ot the endoscopic biopsy forceps. Therapeutic skills like biopsy sampling may also be simulated.

Polyp Cutting

After the lasso tool is placed around the polyp, the wire ensnares the polyp neck. Initally, the neck deforms until the force within the springs reach their yield limit. The deformation is achieved by computing the distance the lasso is interpenetrating the neck, and displacing the neck surface accordingly. Cutting is achieved by computing the intersections of the lasso edge with the faces of the neck and retriangulating the faces as the lasso moves though the neck surface.

Detecting these intersections requires tracking the surface swept by the loop edges and computing the intersection between the swept surface and the faces. The cutting algorithm stores information based on primitive states and not an object-wide state, making it is possible to cut complex surfaces with folds and to form additional cut paths within the same object. Figure 8 demonstrates the cutting procedure as the lasso passes through the polyp surface. Notice how the texture warps before the nodal texture coordinates are updated along the newly created edges.

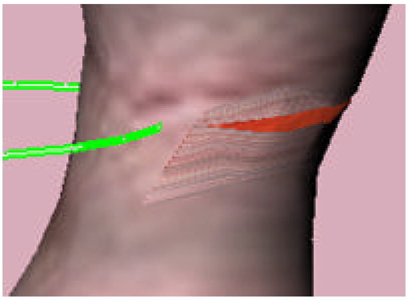

Figure 8. Close up of cutting procedure on a polyps neck, where the lasso-wire passes through the surface.

Haptics Interface

The haptic interface is achieved by using a modified Laparoscopic Impulse Engine (Immersion, San Jose, CA). This simulator uses an off-the-shelf rubber and plastic pelvis model to hide the haptic feedback hardware. We used a handle to support probing and grasping polyps or cutting procedures by adding force-feedback in order to give an impression of the compliance of each procedure. The extension/ retraction trigger was sensed and fed into an analog-to-digital converter to allow programmatic access. In addition, a floor pedal was wired to the system to simulate the pedal used for turning on the current during cauterizing procedures.

The Haptic Device Controller (HDC) is a networked computer that is equipped with custom electronics to control the haptic interface device. This controller reads the haptic device's position and orientation and transmits it over the network via a TCP/IP connection to the simulation server. In addition, it also receives force vector commands from the simulation server over the network and applies these forces to the user. The Haptic Device Controller also performs various safety checks and maintains high-fidelity haptic sensations through force interpolation. By separating the simulation system into two parts, the haptic rendering of forces can progress at the maximum possible rate unencumbered by the cycle time of the simulation.

Figure 9. To grasp a polyp, an endoscopist manipulates the handle on the plastic pelvis model, which hides the haptic feedback hardware.

3 Results

We have assembled a preliminary environment for simulating tasks that are performed in diagnostic and therapeutic colonoscopy. By integrating new CT and MRI data acquisition strategies for colon imaging, segmentation, mesh generation and reduction, we can import a very high-quality geometry into a system that models the colon including pathologies with different physical properties. This system provides for interaction with both non-force-feedback and haptic devices and for display with a stereo workstation monitor or tracked head-mounted display.

This system realistically simulates the score tip of the colonoscope with instrument channel, irrigation, lens and light is modeled and the working channel allows interactions with different instruments as an endoscopic biopsy forceps and a snare (lasso tool) for polyp extraction. Operators begin the procedure by reviewing guided curricula, case histories, and instructions, then perform a simulated polyp extraction and progress to patient specific diagnostic and operative procedures. Later, this patient specific skills are transferred to actual operations. While a complete evaluation is currently underway, initial feedback from clinicians using the system has been positive and validated the colon models, visual display, and force feedback as similar to real procedures but, as expected, also indicated that more refinement of forces and visual appearance is desired before wider deployment.

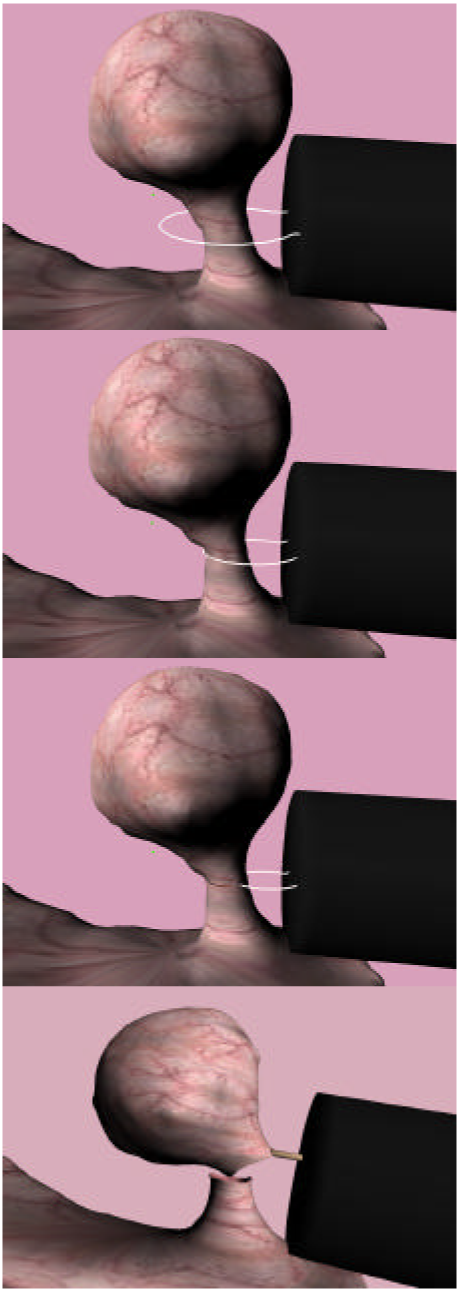

Figure 10 demonstrates four frames of the simulation. In the first frame, the user ensnares the virtual polyp that consists of 4300 faces and 6500 edges. In the next frame, the neck of the polyp deforms until the braking strength changes to the cutting phase. The following frame illustrates the interactive retriangulation of the polyp neck as the lasso moves through it. The final frame shows the user switching to the forceps endoscope tip removing the polyp.

4 Discussion

Virtual colonoscopy techniques for screening and preoperative staging combine volumetric imaging based on MDCT or MR datasets with sophisticated image processing. The recent availability of true isotropic data sets from MDCT examinations, coupled with the development of computer algorithms to accurately and rapidly render high-resolution images in three-dimensions and perform fly-throughs provides a rich opportunity to take this new methodology from theory and preliminary studies to practice. We use these high resolution datasets and have developed a virtual reality system for simulating endoscopy and polyp extraction that can facilitate both the learning process before procedures on patients as well preoperative patient specific simulation for complicated cases. This system enables the trainee specialist to develop, exercise and sharpen his/her colonoscope procedural and therapeutical skills on a virtual sample. Therapeutic skills like biopsy sampling may also be simulated. Future developments include simulating difficult procedures like ERCP. This system can be used to simulate diverse procedures on a variety of specimens in a novel physical environment and hopefully can shorten training periods and reduce complications.

This project addresses the problem of constructing a simulator system for teaching trainee doctors to use flexible endoscopes [13]. Promoting the effective use of the endoscope is of major social importance in preventative medicine as it provides for the early diagnosis and treatment of colonic cancer. Endoscopy has recently been generally recognised as a technique offering considerable advantages over surgery. Computer simulation can provide effective and safe training for endoscopy and thus increase the number of skilled, practising endoscopists. Considerable interest has recently been paid to the improvement of training in medicine, and the role that the computer can play in it, both in the USA and Europe. This project is still the only one of its kind to produce soft tissue simulation while cutting polyps, and the only practical simulator using interactive graphics while modeling colon polyps and tumors with different physical properties for interaction with both non-force-feedback and haptic devices.

Acknowledgements

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