

A Haptic-Enabled Simulator for Cricothyroidotomy

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Abstract. Cricothyroidotomy is an emergency procedure that is performed when the patient's airway is blocked, and less invasive attempts to clear it have failed. Cricothyroidotomy has been identified as an essential skill for military readiness. This training is relevant to more than 40,000 U.S. military medics, and thousands of civilian health care providers. Current training methods use animals, cadavers and plastic mannequins. Animal models do not have the correct anatomy. Cadavers do not have the correct physiology. Mannequins do not adequately cover the full range of anatomical variations. In this paper, we describe our effort to build a computer-based cricothyroidotomy simulator to address these problems.

1 Introduction

Open cricothyroidotomy is an essential skill in emergency airway management. It is the procedure of choice when ventilation cannot be achieved by less invasive methods [1, 2]. This skill has relevance to both military and civilian medical services. For example, cricothyroidotomy is the recommended approach for the management of certain thermal or toxic gas injuries during tactical field care [3]. As another example, cricothyroidotomy may be necessary to secure the airway in gunshot wounds to the face, a situation that can be encountered both during combat and in the civilian emergency room [4, 5].

In cricothyroidotomy, an incision is made in the cricothyroid membrane. A tracheostomy tube is introduced through the incision into the trachea. Air flows through the passage created, permitting the patient to breathe. When performed correctly, the procedure is safe. Current teaching methods use animals, cadavers, or mannequins. These methods have disadvantages. Animals do not have the same anatomy as humans, and their use can involve ethical issues. Cadavers cannot produce an appropriate physiological response. Mannequins and Human Patient Simulators have been used to teach cricothyroidotomy with some success [6, 7, 8]. The latter can provide some physiological response during simulation. However, they require parts that must be replaced after every exercise. They do not bleed convincingly during simulation, and different mannequins are necessary to represent patients with different injuries, body types, and age groups.

Computer-based surgical simulators using a combination of 3D graphics and haptics can provide an alternative. They can contain accurate representations of human anatomy and

physiology. Different patient types can be simulated by loading the appropriate model. More importantly, computer-based simulators can incorporate metrics to measure student performance. Improvements in skill level can be quantified. They also have the potential to incorporate didactic material, and provide real-time feedback on performance. When a mistake is made, students can back up to an earlier stage in the procedure to try again.

In this paper, we describe the ongoing development of a computer-based cricothyroidotomy simulator. A mannequin model is not used. Instead, 3D computer patient models are employed. Haptic and visual feedback is provided using a hand-immersive environment similar to that described in [9]. To date, no comparable computer-based simulator for cricothyroidotomy has been developed.

2 Methods

This section describes the system's hardware, the software components, and our implementation of the steps in the cricothyroidotomy algorithm.

2.1 Hardware

The system is developed on a hand-immersive platform similar to [9]. A cathode ray tube (CRT) monitor generates a 3D frame-sequential image of the virtual patient. This image is reflected off a front-silvered mirror to the user. The user, wearing a pair of CrystalEyes shutter glasses, perceives a 3D virtual image behind the mirror. A Phantom haptic interface device [10] is positioned such that its working volume is co-registered with the visual space. An individual working in this environment can see and feel virtual objects within the working volume. Hand-eye coordination is preserved. We have chosen this configuration as the most natural interface for open cricothyroidotomy. The interface is driven by a PC with dual Pentium IV Xeon 3.02GHz processors, 2Gb of main memory, and a 3DLabs Wildcat 7110 graphics card. The system is capable of driving the visual display at better than 20 frames/sec. The haptic loop runs at 1KHz.

2.2 Software Components

The system was implemented using the ReachIn API [11]. The API manages visual and tactile rendering on the hand-immersive hardware. The API permits software development to focus on developing application specific 3D models and tools, and their interaction. Applications need not be explicitly involved in this aspect, but can override default actions if required. The ReachIn API uses the Virtual Reality Markup Language (VRML) [12] as the basis for its modeling language. Extensions to VRML permit additional properties, such as tissue stiffness, event triggers, and user-defined objects to be defined as nodes and connected to the VRML tree.

In our system, the software components that have been developed include: the graphical user interface, the patient model, and key surgical skill steps. We describe each in turn.

2.2.1 The Graphical User Interface

Fig. 1 illustrates the graphical user interface (GUI). The user sees a virtual patient lying supine. A palette of possible actions appears to the right. Using the Phantom stylus, the stu-

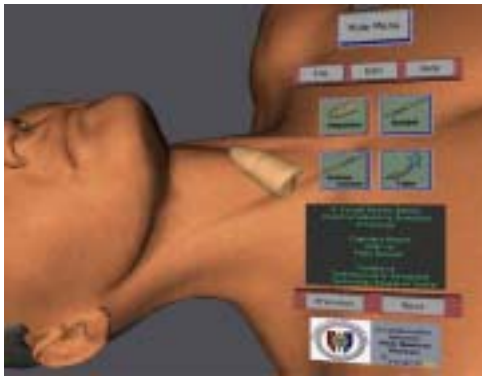


Figure 1: The graphical user interface

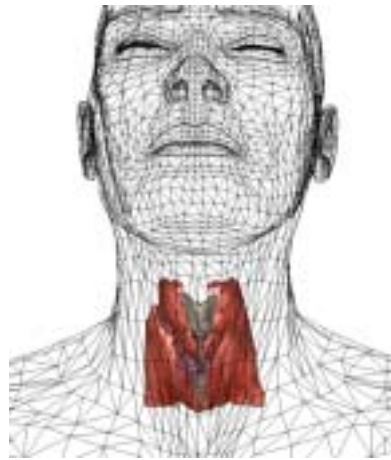


Figure 2: A virtual patient model used during simulation. The skin is represented by a wire frame to highlight the thyroid model.

dent can select from one of several possible actions, including palpation, performing an incision, widening an existing incision, and intubation. In addition, the GUI incorporates various help modes to assist the student in performing the procedure. For example, the student can toggle skin transparency in order to visually locate and study the thyroid.

2.2.2 *The Patient Model*

Patient models are developed in 3D Studio Max [13] and exported as VRML files. Additional properties, such as tissue stiffness, collision response handling, and tool interaction are incorporated in a post processing step. Since the main area of focus is the region around the thyroid, a detailed thyroid model is included. Fig. 2 illustrates.

2.2.3 *Skill Steps*

The surgical algorithm for cricothyroidotomy involves multiple steps. Each step requires a specific skill or action to be performed. Our system implements each step as a separate module. This permits additional modules to be incorporated as needed. These additional steps may represent common variations in performing the procedure, or additional actions that must be performed for patients with unusual injuries. For each module, the surgical instruments used as well as the expected visual and haptic feedback are encoded. Four key steps of the algorithm have been implemented. They are: identification of anatomical landmarks, performing the incision, incision enlargement, and inserting the tracheostomy tube. We describe each in turn.

Landmark identification: Locating the cricothyroid membrane is primarily a tactile task. The surgeon first palpates the neck anteriorly to locate the thyroid cartilage, then moves down until the space between the thyroid and cricoid cartilage is identified. The membrane is located in this space. In our system, the virtual patient model facilitates the practice of this skill. Visually, the student sees the skin on the patient's neck. Beneath the neck is a detailed model of the patient's thyroid. The skin, cartilage, and membrane have different mechanical properties. The student interacts with the model using the Phantom. As the student probes the patient's neck, different levels of stiffness are perceived, corresponding to the different

cartilage structures. Once the correct location is identified, the student can mark the spot before performing the next action.

Making the incision: When an incision is made, the wound opens, the cut bleeds, and resistance is felt as the scalpel passes through skin. In our system, we simulate this using a novel technique described in [14]. Our approach does not require polygon subdivision [15, 16]. Visually, animated textures are used to simulate the appearance of the wound opening and bleeding. The model's topology is unchanged. Haptically, a local model is used to simulate the sensation of cutting with a scalpel. For small, straight-line incisions, this can be modeled using two effects: reaction force and constrained motion. As the scalpel is pushed into tissue, it exerts a reaction force in the opposite direction. In our system we model this force as a function of scalpel depth, position, and the direction of shortest distance to the skin from the scalpel tip. During the cutting process, tissue surrounds both sides of the scalpel blade. This constrains blade motion in a plane that includes the cut. We model this as a force that is exerted whenever the scalpel drifts from the cut-plane. More details can be found in [14].

Incision enlargement: During an emergency cricothyroidotomy, the back of the scalpel blade is often used as an expedient to enlarge the initial incision. We model the visual and haptic effects of this step in a fashion similar to that used during incision. The appearance of the wound widening is accomplished by updating the texture map over the incision with a sequence of images. Haptic feedback is accomplished with a local model that constrains the instrument to penetrate the skin at a single point. Resistance to insertion is modeled by a reaction force, similar to that described previously.

Intubation: To simulate the resistance of inserting the tracheostomy tube, a simplified model of the trachea is used to provide haptic response. This model is not rendered visually. The original model could not be used because it contained too much detail for real-time collision detection and response at haptic rates. During intubation, collision with the haptic model was determined at five evenly spaced points along the tube. For each point, if a collision occurred, the reaction force was noted. The resistance on the tube was then taken as the vector sum of reaction forces.

3 Results

Our implementation currently permits students to practice the basic skill steps in cricothyroidotomy. In the simulation, the student, wearing CrystalEyes shutter glasses, sees a 3D rendering of a virtual patient. A menu of actions appears beside the patient. The student uses the Phantom haptic interface to interact with the environment. The student selects the appropriate action to be performed. Based on the action selected, the Phantom's stylus is replaced by various surgical instruments. For example, when making an incision, the stylus is replaced by a scalpel. As the student performs the cut, the wound opens and bleeds. The student also receives haptic feedback via the Phantom. The extent of bleeding depends on the depth of the cut. For example, if the student exerts a lot of force and creates a deep cut, the wound bleeds profusely. Figs. 3(a), 3(b), and 3(c) illustrate some other actions being performed.

Preliminary assessments by surgeons familiar with the procedure have been favorable. The evaluators commented favorably on the accuracy of tactile response during palpation, incision, and intubation, as well as the realistic bleeding.

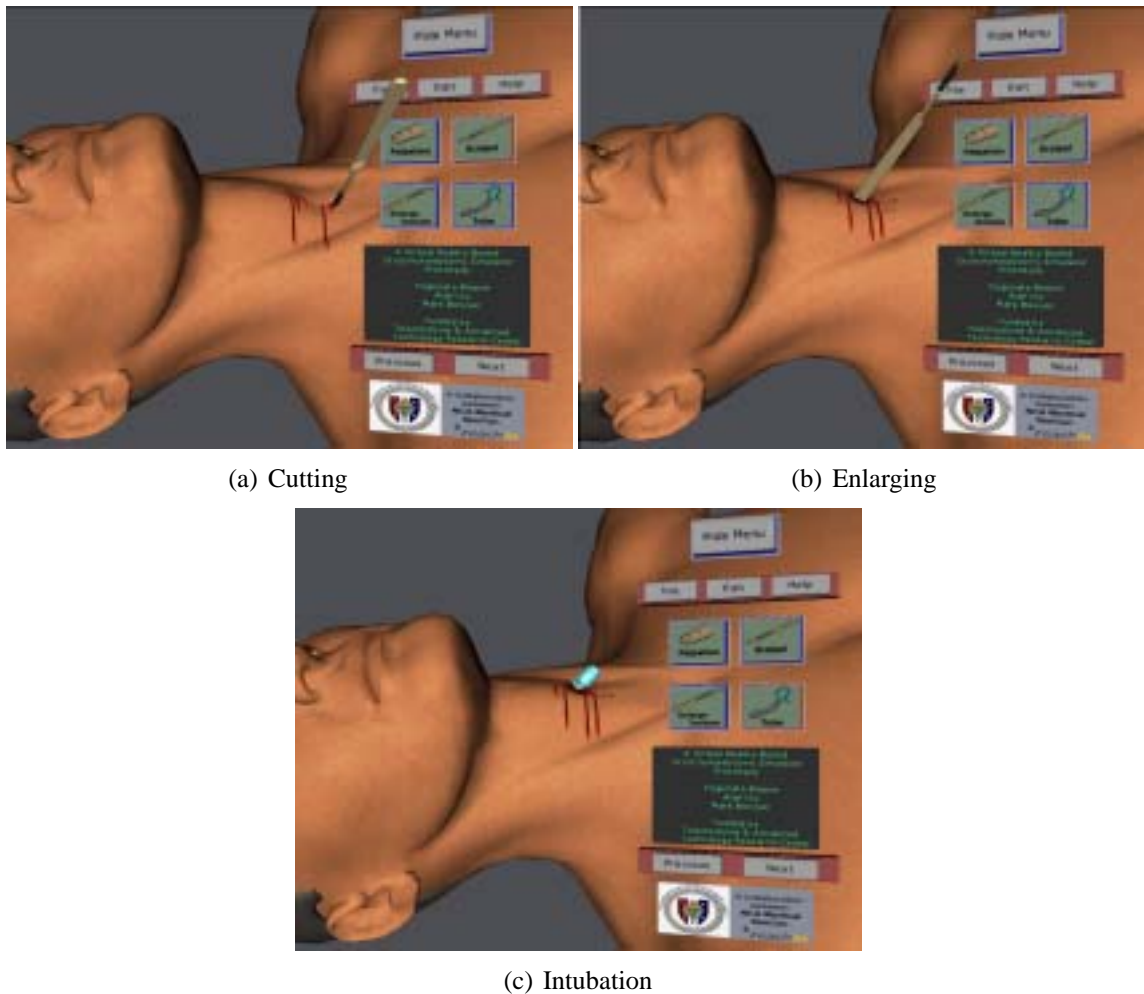


Figure 3: Skill Steps in the Cricothyroidotomy Simulator

4 Discussion and Conclusion

In this paper, we described our cricothyroidotomy trainer currently under development. Unlike current efforts, our approach uses a hand-immersive display with both visual and tactile feedback. Our system is an improvement, as using virtual models enables students to practice on a wide range of patient types using the same hardware. Technical achievements include the use of animated textures and local haptic models for simulating incisions and instrument insertion [14]. Previous attempts have focused on incorporating the cut in the patient model. In those attempts, polygon subdivision is required, which increases model complexity. Moreover, the resulting polygons are frequently suboptimal in shape. Degradation of visual and haptic rendering performance can result. Our approach does not require polygon subdivision. The model's complexity remains constant, and visual rendering efficiency does not degrade. Using a local haptic model permits haptic feedback to be decoupled from the model's topology, and is computationally efficient.

The system can be used as a teaching aid in its present state. However, it lacks the ability to independently instruct the student in the procedure, and metrics to measure student performance have not been incorporated. These shortcomings will be addressed in the

ongoing development effort.

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