A Simulation-Based Training System for Surgical Wound Debridement

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Abstract. A simulation-based training system for surgical wound debridement was developed and comprises a multimedia introduction, a surgical simulator (tutorial component), and an assessment component. The simulator includes two PCs, haptic device, and mirrored display. Debridement is performed on a virtual leg model with a shallow laceration wound superimposed. Trainees are instructed to remove debris with forceps, scrub with a brush, and rinse with saline solution to maintain sterility. Research and development issues currently under investigation include tissue deformation models using mass-spring system and finite element methods; tissue cutting using a high-resolution volumetric mesh and dynamic topology; and accurate collision detection, cutting, and soft-body haptic rendering for two devices within the same haptic space.

Keywords. Surgical debridement, wound debridement, training

Introduction

In 1999, The Institute of Medicine issued a report estimating that as many as 98,000 people die from errors in hospital settings each year [1]. Subsequently, the AMA's Accreditation Council for Graduate Medical Education limited the time that residents can be required to work to 80 hours a week. Although this action was intended to improve patient safety, it also reduced the number of patient-contact hours needed to train residents. Thus, medical educators are looking for alternative methods to provide residents with meaningful learning experiences. Many are turning to simulator-based training to meet that need [2, 3].

In many high risk domains (e.g., aviation, military training, process plant control, etc.), simulators are routinely used to allow trainees to acquire and practice skills in a safe and controlled environment [4]. One of the important benefits of this approach is that trainees can acquire much of the fundamental knowledge and skills needed to perform elementary activities largely on their own without the need for constant supervision by an instructor. Accordingly, that approach was adopted as the guiding principle behind the development of the surgical wound debridement simulator system.

1. Wound Debridement

Wound debridement refers to the process of removing necrotic, devitalized, or contaminated tissue and/or foreign material to promote healing [5]. In surgical debridement, a scalpel or scissors is used to cut away the necrotic tissue. Wound debridement is a minor surgical procedure, but one that is performed by surgeons, physicians assistants, surgical assistants, nurses, and military medics and corpsmen. At present, this procedure is typically learned with actual patients under the guidance of a more experienced physician.

2. The Simulation-Based Training System

A simulation-based virtual reality (VR) training system for surgical wound debridement was developed to provide trainees with the fundamental knowledge and skills to perform the procedure through self-instruction and practice, thereby eliminating the need for one-on-one instruction. The system comprises a multimedia introduction, a surgical simulator (tutorial component), and an assessment component.

2.1 Multimedia Training Component

The multimedia training component describes varieties of wound categories (e.g., burns, lacerations, etc.); methods of debridement (e.g., sharp, mechanical, etc.), and equipment/materials used in the procedure. This module provides the pedagogical context for skills training and assessment, linking together all of the required elements for mastering the procedure. Pedagogical material and methodologies have been researched (e.g., [5]) and design stems from training requirements and iterative development through consultation with domain experts.

Elements are arranged in sequential order to support educational advancement of the novice; however, the navigational design permits all menu items to be accessible at any time thereby also supporting the experienced user. Further, freedom to run the multimedia component on a platform other than the one used for the skills training makes it possible to support multiple users simultaneously.

2.2 Virtual Agent

A software virtual agent is included and performs the role of an instructor by providing verbal guidance and assessment feedback (see Figure 1). Designed to be comprehensive in order to reduce the need for a more senior instructor, the software addresses the patient's condition, initial description of the injury, and provides instruction on operation of the simulator. Specific instructions cover the removal of foreign objects with forceps, scrubbing with a brush, rinsing with saline solution, and the maintenance of sterility. The trainee is prompted to move on when the current stage is completed satisfactorily. The current software implementation for the agent uses Haptek[1] and NeoSpeech[2].

2.3 The Simulator: General Description and Technical Implementation

A prototype of the wound debridement trainer has been developed using the Derivative API[3], for fast initial testing of user and design requirements. OpenHaptics Toolkit

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[1] Haptek, *PeoplePutty, Haptek Player SDK, Haptek Player* viewed 10-17-05, http://www.haptek.com
[2] NeoSpeech, *Kate,* viewed 10-17-05, http://www.nextup.com/neospeech.html
[3] Derivative Inc. *Touch Designer,* viewed 10-17-05, http://www.derivativeinc.com/

(Sensable) interfaces with a haptic device (Omni or Premium) for wound interaction while viewing it on a Reachin display device[4][5]. A parallel research effort with an open architecture uses OpenSceneGraph alongside an FEM physics approach for increased flexibility and realism in the training application (see Section 3.2).

2.3.1 The Anatomy and Wound

The simulator provides training on a shallow laceration wound to the thigh caused by a motorcycle accident. Our wound research focuses on the extremities and the leg model is derived from the National Library of Medicine's Visible Human Project [6]. Axial anatomical imagery is manually segmented, registered, and triangulated polygonal surface meshes of relevant objects are constructed. Subsequent to viewport culling the skin mesh, as used in our prototype, is approximately 1000 polygons.

Foreign material embedded in the wound is modelled both geometrically and as surface texture. It is possible to render a high degree of dirt without an increase in computational expense as would be the case if debris implementation were pursued solely as geometry. Currently the majority of the debris (dust, dirt) is rendered as texture on the wound surface geometry while larger objects are polygonal meshes.

The simulation uses several textures for a range of the debridement processes (Figure 3). Each polygon in the mesh is handled separately in terms of texture image while texture coordinates remain constant. The intersection between an instrument and surface polygon results in a substitute texture being called for that polygon.

Bleeding is implemented using a particle system. Particles are created only when instruments intersect with polygons within the wound area. Small amounts of gravity and randomness are added to particle motion upon collision with the wound surface their reflecting vector is reduced normal to the collision. As a result, the particles slow down and approach the wound surface geometry over the duration of their lifespan.

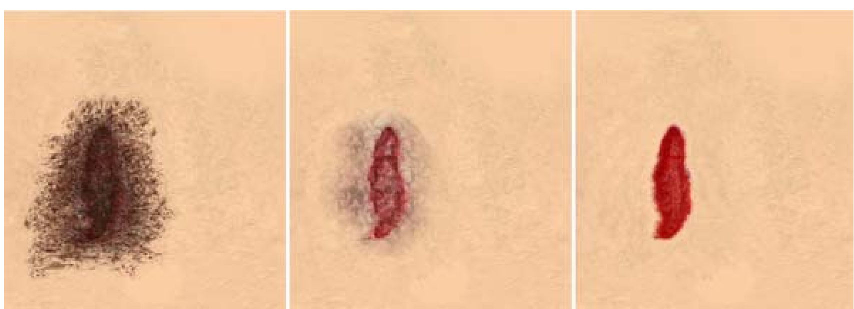

Figure 3. The concept of using textures to model debris.

2.3.2 Graphics and Haptics Simulation within the Prototype Application

A mass-spring simulation implemented within the prototype application and Derivative API drives graphics deformation. Approximately 200 nodes are deformed to restrict

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[4] SensAble Technologies *OpenHaptics Toolkit*, *Phantom Premium, Phantom Omni*, viewed 10-17-05, http://www.sensable.com

[5] Reachin Technologies *Reachin Display*, viewed 10-17-05, http://www.reachin.se/

the simulation to those that fall inside the wound area (the remainder are fixed). All nodes have the same mass and drag and the spring is kept fairly stiff for stability.

A static, haptic thigh model where topological changes from the mass spring model in Derivative are not updated has been implemented. Users do not readily perceive the limited synchronicity between the graphics and haptics which results in an economic and effective implementation. The haptic rendering also supports grabbing points on both the deforming graphic and the haptic meshes (e.g., with forceps, see Figure 4). Force is subsequently applied and the user feels tension through the haptic device. Releasing the tissue updates the graphical points back to their starting position.

Both graphics and haptics applications of the simulator will run on a single laptop computer (i.e., with 3.2 GHz CPU; 1GB RAM; GeForceFX Go 5700). Running in parallel, the applications average 60Hz for graphics and 300Hz for haptics.

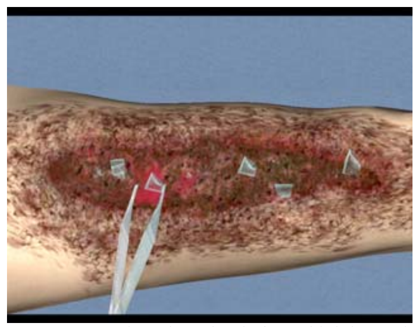

Figure 4. Removing glass shards from thigh laceration.

3. Ongoing Research and Development

3.1 Assessment

At present, assessment is limited to the amount of foreign material successfully removed from the wound and the needed to perform the procedure. The next generation will include assessment modules for the didactic content addressing preoperative and postoperative care, performance-based feedback during the tutorial, summative feedback at the end of the tutorial, and assessment information for either the trainee or instructor. Performance-based assessment will target two types of errors. One set of errors is intended to be "recoverable". For example, removal of a very large shard of glass from the wound could cause a significant amount of bleeding. It would then be necessary for the trainee to stop the bleeding and proceed with the debridement. The second type of error is intended to be "unrecoverable". For instance, the trainee might damage a major blood vessel or nerve. At this point the simulation would terminate and feedback would be provided that describes the seriousness of the error, why it occurred, and how to avoid it in the future.

3.2 Development Platform

There are many fundamental challenges to developing a simulation system for an open procedure like surgical debridement; advanced methods are desired to tackle these challenges. To address the issues in the current prototype using the Derivative API, a new solution employing more capable and flexible technologies is currently under research and development. The following briefly describes several major components under research and development:

- Object oriented software design and development are employed to ensure software quality, ease of component integration, future extension, and maintenance. Major classes of the surgical debridement simulator include tissue and instrument supporting the simulated objects and mass spring and finite element models underlying the physics-based models. Some auxiliary classes are also developed to facilitate computation, such as topology processing. In addition, the software components are not tied to a specific operating system specific and facilitate portability to other platforms.
- OpenSceneGraph, an open source high performance 3D graphics toolkit, is utilized for developing the visualization component of the debridement simulator. Utilizing scene graph technology and the latest OpenGL 2.0 graphics, OpenSceneGraph has strength in performance, productivity, portability, and scalability. A variety of models are utilized for different computations. Volume mesh is used by tissue deformation and tissue cutting simulation, while surface mesh used by irrigation simulation and collision detection. For computational efficiency, instruments are represented by a line segment or segments enclosing them for collision detection purposes.
- Removing necrotic or contaminated tissue with a scalpel or scissors is a critical procedure that differentiates between surgical debridement and other debridement approaches. Thus, simulation of tissue cutting in a surgical debridement simulator is essential. To effectively model and simulate the cutting procedure, a volume mesh is utilized to represent the wound region on the thigh. A surface mesh is extracted from the volume mesh to render the thigh graphically. Tissue cutting is simulated by deleting volume elements in contact with the cutting instruments, with color images from the visible human data set rendered as 3D textures.
- Mass-spring system and finite element method (FEM) approaches are implemented to simulate soft tissue deformation. Research is underway to build fast computational schemes to improve real-time performance for fast FEM computational methods, rapid neighborhood construction, and a hybrid structure of Mass-spring and FEM.
- XML, a simple and very flexible markup language, is selected as the file format to store the graphical and physical properties of the thigh model, including geometry, texture maps, topology, and FEM parameters. XML writer and reader programs have been developed to create and parse XML files.

The finite element code developed for the wound debridement application computes the 3D volumetric deformation of the leg model based on the displacement of a few surface nodes as determined by the collision detection module. The current model assumes all materials are either linear elastic or rigid. Rigid materials, for example bones, can be represented by applying 0-displacement boundary conditions to an appropriate subset of the model's nodes. The stiffness of elastic tissues in the model can be varied according to segmented tissue type.

The finite element code was written specifically for the purpose of interactive simulation. It makes use of sparse matrix data structures and efficient LASPACK sparse matrix solution routines. Incremental updates to the stiffness matrix are made as the model mesh is cut during the simulation. The finite element code provides as output: (1) the displacement of every node in the model, and (2) the force vector in effect at every node. The force vector that is computed at the point of contact between a surgical instrument and the deformable model defines the force that should be haptically displayed to the user. Currently, the finite element code computes a deformation solution at a rate of 60-70 Hz for a model with 400 elements and 20-30 Hz for a model with 1100 elements which is sufficient for graphics. Further optimization of the code to improve efficiency and a parallel implementation is planned.

4. Conclusion

A simulator-based training system was developed for surgical wound debridement. The goal was to create a system that would allow health care providers to acquire the fundamental knowledge and skills to perform the procedure through self-instruction. The current system contains a multimedia component for didactic material, a tutorial, and VR-based simulator with haptic feedback. Trainees can learn to clean to a wound and remove foreign objects. However, many technical challenges remain to improve the realism of the graphical and haptic displays. These include: 1) more realistic tissue deformation using mass-spring and finite element models, 2) better collision detection, 3) incorporating tissue cutting, and 4) adding two-handed haptics because debridement is typically performed using both hands. It is expected that solutions to these challenges will not only help to refine the physics-based models underlying the anatomy and physiology represented in the system, but will also expand the variety of wounds that can be included in the set of training cases.

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