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Development and Evaluation of an Epidural Injection Simulator with Force Feedback for Medical Training

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Abstract. Performing epidural injections is a complex task that demands a high level of skill and precision from the physician, since an improperly performed procedure can result in serious complications for the patient. The objective of our project is to create an epidural injection simulator for medical training and education that provides the user with realistic feel encountered during an actual procedure. We have used a Phantom haptic interface by SensAble Technologies, which is capable of three-dimensional force feedback, to simulate interactions between the needle and bones or tissues. An additional degree-of-freedom through an actual syringe was incorporated to simulate the "loss of resistance" effect, commonly considered to be the most reliable method for identifying the epidural space during an injection procedure. The simulator also includes a new training feature called "Haptic Guidance" that allows the user to follow a previously recorded expert procedure and feel the encountered forces. Evaluations of the simulator by experienced professionals indicate that the simulation system has considerable potential to become a useful aid in medical training.

1. Introduction

An epidural injection is a commonly performed procedure for pain relief. For example, it is used to reduce pain during labor and delivery, and to reduce pain in the lower back and legs from nerve irritation such as from a herniated disc. Epidural injections require a high level of precision and skill from the administering physician. While inserting the needle into the epidural space, one must be careful so as to not perforate the dura matter, a tough fibrous layer that covers and protects the spinal cord and its nerves, as this would result in complications such as spinal headache and CSF leak that can lead to life threatening infections on rare occasions.

When guiding the needle into the epidural space, physicians depend on one or more of several feedback cues, such as the resisting forces occurring at the needle or x-ray imaging (fluoroscopy). Another important method to identify the epidural space is the so-called "loss of resistance" effect. After the needle tip has entered the supraspinous ligament, a syringe filled with a small amount of air or fluid is attached to the needle. While the needlepoint is still in the dense ligaments, fluid or air injection is not possible.

However, as soon as the needle enters the epidural space, a relatively low pressure environment, a significant drop in resistance is encountered and the fluid or gas can easily be injected.

Currently, residents in post-graduate medical training and other trainees learn to administer epidural injections by performing supervised procedures on real patients or less frequently on cadaver specimens. Several attempts have been made to create a computer-based simulator for training in this procedure, typically using one-dimensional haptic feedback devices [1-5]. At Millersville University, Pennsylvania, a three-dimensional simulation of a similar medical procedure, lumbar puncture to obtain cerebro-spinal fluid, has been developed [6]. A training program developed at the Manchester Visualization Center that uses a Logitech Wingman Force Feedback Mouse can be downloaded from the World Wide Web [7].

We have created an epidural injection simulator for medical training that is capable of three-dimensional force feedback and incorporates an additional degree-of-freedom through an actual syringe to simulate the "loss-of-resistance". As a new training feature, we have developed a method of recording the forces used by an expert, which can be played back to the trainee for haptic guidance. Experienced physicians in pain management and anesthesia rated the accuracy of our simulation and its utility as a training tool. Our paper concludes with preliminary results of these assessments.

2. Methods and Tools

Needle-Tissue Interaction

Our simulator uses a Phantom haptic interface by SensAble Technologies and its software toolkit GHOST. The lower vertebrae L4 and L5 have been modeled as well as the important soft tissues for an epidural injection, namely skin, subcutaneous tissue, supraspinous ligament, interspinous ligament, ligamentum flavum, epidural space, dura mater and subdural space. The geometrical models of the virtual objects are stored as Open Inventor files.

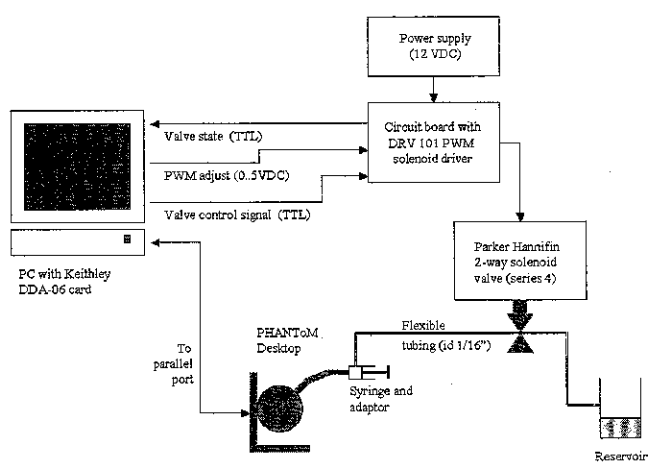

Figure 1. Schematic overview of simulator setup

Collisions between the needle tip and the tissue layers are detected with the "Neighborhood Watch" algorithm [8], an efficient method that makes use of oriented bounding boxes for initial contact recognition and a hierarchical representation of the geometry for collision detection once a preceding contact point is known. The haptic representation of the vertebrae is given by a spring-damper model. A piecewise linear series of Voigt elements has been proposed in [5] to govern the feedback forces in viscoelastic tissues. We have generalized this model for the three-dimensional case and added a set of logical rules to apply different forces when the needle is advanced or withdrawn from already ruptured layers. Internal Coulomb friction has been implemented and an additional force component based on a spring-damper model limits the lateral movement of the needle in the tissues.

In the current version of our simulator, the parameters of the tissue layers are determined following a perceptual approach. Experienced professionals adjust the model so that the feel of the simulated forces resemble the feel encountered in a real epidural injection. For this purpose, slider controls have been established to manipulate the coefficients of each tissue during run-time, such as the thickness of the tissues, spring and damping constants, widths of elements in the Voigt series and friction coefficients. The sliders may also be used for creating various virtual patients with different tissue characteristics. If empirically determined tissue properties are available, they can be easily incorporated into the model and simulation.

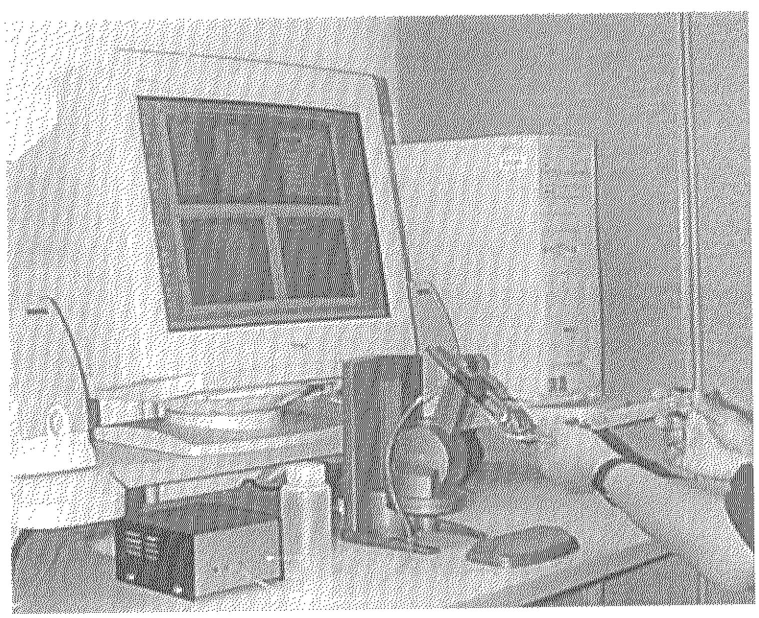

Figure 2. Epidural Injection Simulator with attached syringe

Loss of Resistance Simulation

In order to employ "loss of resistance" method, a syringe filled with either air or water can be attached to the Phantom at any time during the simulation. A two-way solenoid valve controls the flow through the syringe. The solenoid is driven by a pulse-width modulated input signal, thus allowing adjustment of different flow rates. In the current version of the simulator, the valve is only switching between two states, enabling flow when the needlepoint has entered the epidural space and closing the valve otherwise.

Visualization

During a training session, simulated front and lateral view x-ray images that show the current needle position can be displayed. The user can also select a 3D visualization of the vertebrae and tissue models that form the haptic scene.

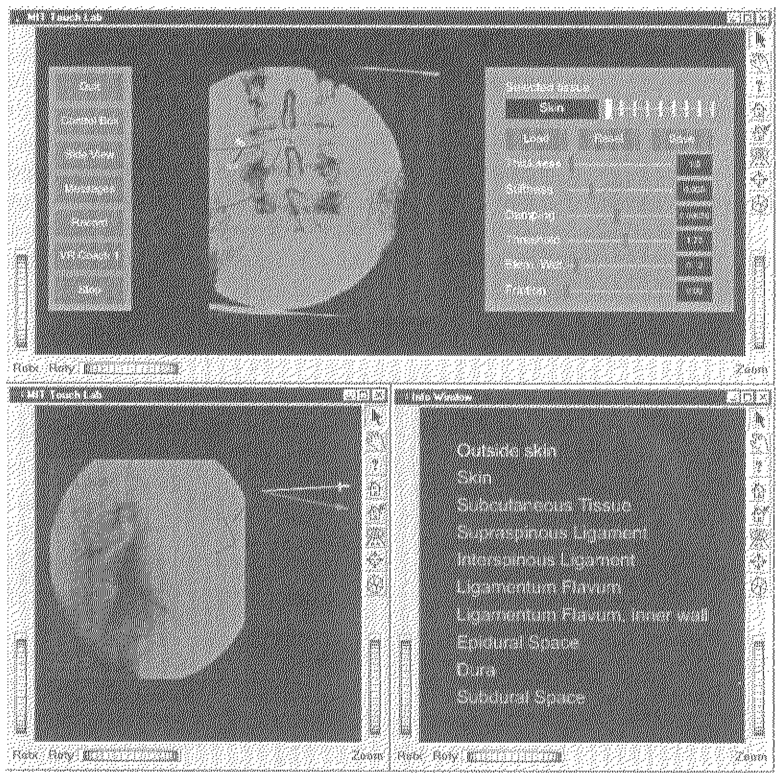

Figure 3. Screen capture with slider controls and tunnel guidance

Training Features

When starting the simulation, the trainee chooses the position of the virtual patient. In the current version of the simulator, seated or prone (lying with front of body facing downwards) positions are available for selection. In accordance to the experience of the user, different levels of additional visual and audio information can be provided during training. For example, a text window indicates the tissue in which the epidural needle is currently placed or the computer can announce important landmarks by playing corresponding audio files. These features should be gradually disabled as the trainee proceeds to more advanced training phases. The simulator also allows for recording of injection trials for further evaluation of the trainee's performance.

Related to recording of injection trials is "Haptic Guidance". The basic idea behind this feature is that a virtual instructor guides the hand of the novice through the injection procedure. We have experimented with several versions, two of which were found most promising. In the first approach, the simulator displays a second ("guiding") needle on the screen that moves along the same path and with the same speed as an expert in a previously recorded trial. If the user's needle position exactly matches the position of the guiding needle, the user will feel the same forces as the expert while the injection procedure was recorded. If there is a discrepancy between the actual and the guiding needle, the "virtual instructor" applies a force to pull the trainee back to the recorded trajectory. If the discrepancy exceeds a threshold value, the guiding needle changes its color and replay is paused until the user returns to the recorded position.

The second implemented version of haptic guidance discards the time-dependency of the recorded data, i.e. the user can perform the injection at his or her own speed. Here, the complete recorded path of the expert is displayed graphically and the movement of the needle is limited to the recorded trajectory, thus allowing the user to solely concentrate on the encountered tissue forces. "Tunnel Guidance" might be a suitable term to describe this feature.

3. Expert Evaluation and preliminary results

Experienced anesthetists and pain management specialists at UT Southwestern Medical Center at Dallas have evaluated the simulation in regard to its accuracy and utility as a training tool. Further evaluations are currently taking place at the MIT Laboratory of Human and Machine Haptics.

On a ten-point scale with ten indicating the best possible rating, the experts rated the likeliness of the simulated tissue forces at an average value of 6.4. The highest ratings (8.5) were achieved for the simulation of the "loss of resistance" effect. All interviewed experts indicated, that the "loss of resistance" was also the most reliable feedback in real-life procedures. Overall, the subjects rated the utility of the simulation as a training tool at 7.4.

4. Future Work and Conclusions

A shortcoming of using the Phantom Desktop model for our simulator is the inability to control the orientation of the needle. However, this limitation can be overcome by using haptic interfaces with full force and torque feedback, such as the Phantom 6DOF. Another promising method we have used to solve this problem in other contexts is the use of two Phantoms and ray-based haptic rendering techniques that have been developed at the MIT Touch Lab [9, 10].

Further work on the simulator will include improvement of the tissue models in regard to the feedback forces and the tissue geometries, and the attachment of a human low-back mannequin, as suggested by several interviewed experts. Overall, the expert feedback was encouraging and the preliminary evaluation results indicate that the simulator has considerable potential to become a useful aid in medical training.

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