Design of High-Fidelity Haptic Display for One-Dimensional Force Reflection Applications

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ABSTRACT

This paper discusses the development of a virtual reality platform for the simulation of medical procedures which involve needle insertion into human tissue. The paper's focus will be the hardware and software requirements for haptic display of a particular medical procedure known as Epidural Analgesia. To perform this delicate manual procedure, an anesthesiologist must carefully guide a needle through various layers of tissue using only haptic cues for guidance. A simplifying aspect for the simulator design, all motions and forces involved in the task occur along a fixed line once insertion begins. To create a haptic representation of this procedure, we have explored both physical modeling and perceptual modeling techniques. A preliminary physical model was built based on CT-scan data of the operative site. A preliminary perceptual model was built based on current training techniques for the procedure provided by a skilled instructor. We compare and contrast these two modeling methods and discuss the implications of each. We select and defend the perceptual model as a superior approach for the epidural analgesia simulator.

Introduction

Several research labs and small companies around the country are currently involved in projects aimed at generating hardware and software to teach medical procedures through realistic computer simulation..[1,8] Human interface products which track the activities associated with certain medical procedures and provide for interaction with computerized tissue and organ models are already appearing on the market. A Laparoscopic Surgery Simulator from Immersion Corp. is an example of one such product. This tool allows a user to wield surgical tool handles and perform the manual manipulations associated with laparoscopic and endoscopic surgery. Simulators which can also provide haptic feedback to the user yet which meet low cost requirements are likewise under development. Sometimes called force reflecting interfaces, these simulators allow for interaction between user and model which include power exchanges, timed and governed to enhance not visual, but mechanical realism. A Catheter Insertion Simulator from Immersion Corp. falls into this category. This devices allows a user to insert a catheter wire into a virtual patient while the computer tracks the wire's feed and spin. In addition to monitoring manipulations, the computer can command a resistance force to the wire to simulate the forces generated when a catheter interacts with body tissue. The result is a human interface platform capable of providing a realistic representation of the manual task and which can be used for training medical professionals.

A product currently under development is the Virtual Epidural Simulator which is a single degree of freedom force reflecting interface designed specifically to provide users with realistic simulation of the medical procedure known as Epidural Analgesia. In addition to the physical hardware for haptic display, this project also requires the development of software techniques for generating the haptic representation of a needle passing through layers of tissue. After briefly introducing the hardware design, this paper will address the fabrication of models for simulating the haptic aspects of the epidural procedure. We will pay particular attention to the need to balance engineering and psychophysical considerations in the design of these models. Two approaches to the process of building models will be highlighted. We call the two approaches physical modeling and perceptual modeling. Running commentary will be provided on each presented model as to whether it fits into the physical or perceptual model paradigm.

We hope that to emphasize the modeling process in the presentation of these models will prove useful. Although certainly we don't expect to be able to come up with directives about which modeling approach is appropriate at any given time, we do hope to spur the development of further design tools by elucidating the various approaches to the process of model construction. After presenting some further background, this paper will introduce the preliminary hardware design, discuss the generation of some design parameters, present a physical and then a perceptual model, and finally discuss future model development efforts before summarizing.

Background

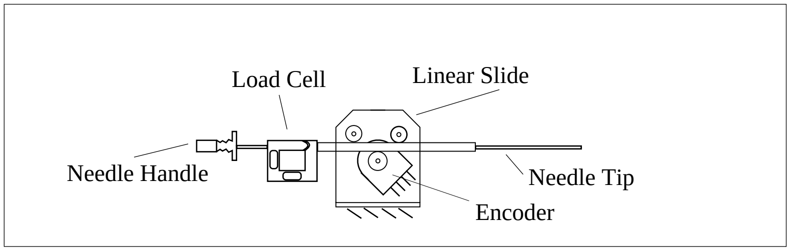
Epidural analgesia is one of the most frequently used techniques for the prevention of pain during surgery. The procedure involves the injection of a local anesthetic or an opiod into the epidural space of the spinal column. Once inserted, the needle does not change direction, its motion is constrained to a line by the dense ligaments. Nevertheless, it is a delicate manual operation. The anesthesiologist must insert a catheter into the epidural space using only haptic cues for guidance. As the needle passes through various tissue layers, a varying insertion force is detectable by feel. By constantly comparing this feel to a mental map of the anatomy and an associated map of expected feel, it is possible to a maneuver the needle into the correct space without damaging the spinal chord. All practitioners of the epidural process must possess this detailed mental map of the needle/tissue mechanical interaction with its associated haptic cues at the needle handle. No visual cues are available since the needle's path is hidden below the surface of the skin.

While epidural analgesia is a common procedure with wide-spread clinical use, current techniques for training students to perform this procedure can be difficult for both student and instructor. The problem is that there is no effective way for students to develop the required mental model of the haptic landscape without practicing the manual insertion on actual live patients. This creates a dangerous situation for patients, a stressful learning environment for the student, and a teaching process which requires instructors to spend much time performing interactive supervision. What is needed is an off-line simulation environment in which students can repeatedly practice the procedure and develop the manual skill without endangering patients and without requiring constant instructor supervision. To meet this need, Immersion Corp., in collaboration with researchers at Ohio Supercomputer Center and Ohio State University Medical Center, is working on a realistic virtual simulation of the epidural procedure. This DOD funded project focuses on developing hardware and software which can reproduce the haptic sensations associated with epidural needle insertion so realistically that it can be used as an effective teaching tool.

The proposed system, known as the Virtual Epidural Simulator, would include a force-reflecting interface which generates the appropriate haptic cues associated with needle penetration of the various layers of biological tissue. It will provide a trainee with a believable, non-threatening environment which encourages the free exploration of the many variances confronted in administering a lumbar epidural. Such interaction and exploration with a simulator should increase the resident's understanding of the anatomy and the intricacies encountered in the epidural procedure. It is hypothesized that such a training environment will reduce resident anxiety and limit the number of trials required to learn to successfully deliver regional anesthesia through the epidural method.

Hardware Description

The hardware for this project is made up of two parts: Haptic Sensing Hardware and Haptic Feedback Hardware. Basically, force and position sensing hardware is needed to devise models to be used in the position sensing and force producing feedback hardware.


Haptic Sensing Hardware

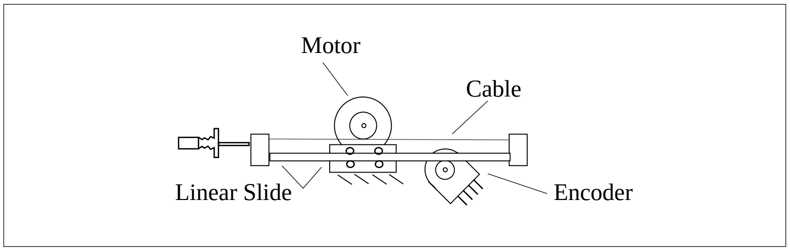

Haptic Feedback Hardware

Figure 1: *Hardware*

Figure 1 shows both the haptic sensing hardware and haptic feedback hardware. The haptic sensing hardware is essentially an instrumented epidural needle. The epidural needle has been mounted on an extra long light-weight handle which is constrained to linear motion without twist by a set of high quality bearings. A small strain gage outfitted load cell which has been electro-discharge machined out of aluminum comprises the force sensor. The amplification circuitry is located right on the load cell on a surface mount printed circuit board. An in-house design 16-bit A/D converter and a low-cost digital IO card allow for acquisition of the force signal by a 486DX2-66 PC. Finally, a 1024 count/revolution rotary encoder with a friction drive wheel on the needle handle is responsible for transducing the position of the needle.

The hardware for the haptic feedback product is made up of a linear slide motorized through a capstan drive by a low-inertia precision motor. A highly flexible steel cable takes three turns around a screw pulley on the motor. For simplicity and low cost, we have decided not to include a force sensor in the final product.

Therefore, measured force will not be available for use in a control law or table lookup scheme. An encoder is again responsible for tracking position of the slide. To minimize inertia, the rod itself moves and the platform is fixed.

The haptic sensing and feedback hardware is used in three configurations. The sensing hardware is used alone with tissue substitue samples to generate simulation models. The sensing hardware is then used together with the feedback hardware to test candidate models. Finally the feedback hardware alone will constitute the simulator.

C++ code for Windows on the PC is responsible for closing the control loop and supporting a full graphical user interface for development and product use. Eventually, the system will include a graphics workstation for the visual presentation of a virtual needle and CT-scan images.

Design Parameter Generation

Already the hardware has proven itself inadequte. It has become apparent that the mass of the force sensor on the needle masks a significant portion of the feel of inserting a needle into a pear. See the Perceptual Model section below for a discussion of the importance of the pear. Quick experiments with naive subjects showed that the ability to differentiate a pear from a tomato was degraded by the presence of the force sensor on the needle. Since the stiffness of the force sensor is very high, its mass must be culprit in the masking effect observed. A simple lumped-parameter mass spring model of the needle in the grip of a trainee has been used to show that indeed the mass of the force sensor must be smaller in the next design. Figure 2 shows some experimental data taken to characterize the stiffness of a typical needle handle grip. The measured force is plotted against measured displacement. The slope of a line fit to the data estimates the stiffness at 15,000 N/m. Note that more information such as damping is also available from this data, but a simplistic model is deemed sufficient for the present purposes. This stiffness value used in two mass-spring models, one with and one without the mass of the force sensor gives two approximate cutoff frequencies. The addition of the 28 gram force sensor to the 3 gram needle would then account for the lowering of a cutoff from 2200 Hz down to 700 Hz.

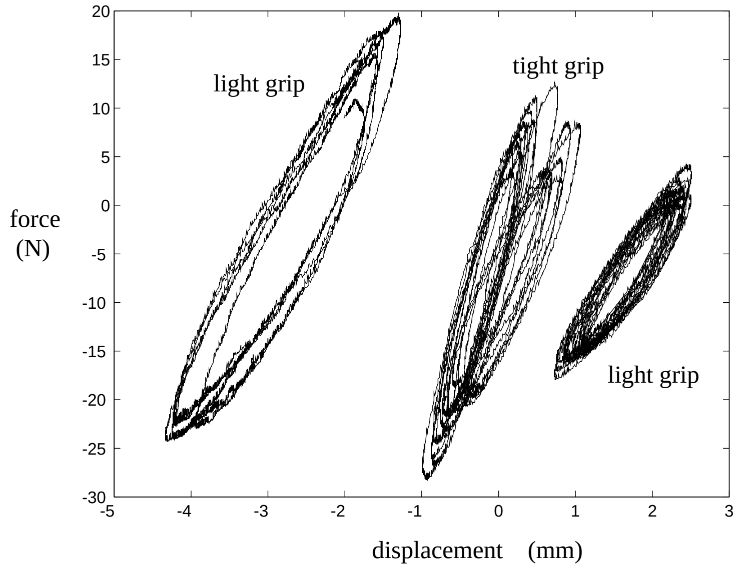


Figure 2: *Grip Stiffness Characterization*

We are not ready to conclude that vibration frequencies in the 700-1000 Hz range could account for the masking effect observed, but this ballpark analysis does suggest that the presence of the force sensor could be attenuating valuable frequency information within the range of human haptic sensitivity. Further experiments with an accelerometer are underway to come up with solid design parameters for a suitable design of the haptic sensing hardware.

Certainly the force feedback hardware introduced above will not have a frequency production capability above 50 Hz. In order to produce such frequencies for haptic display, we are proposing the use of a vibrotactile display such as that developed by Howe and Kontarinis.[4,5] A small 'proof mass' actuated by a tiny voice coil motor could be driven with a waveform containing the high-frequency information.

Physical vs. perceptual modeling

When trying to replicate the forces generated when a needle passes through the various layers of tissue during an epidural procedure, there are several possible approaches one can pursue. The model or control law which will govern the force generated for the user to feel will take on one of a few forms. It may be implemented as a lookup table, an equation, or even as a differential equation within a numerical integration scheme.[2] In the following sections of this paper, we will present several preliminary models which we have used to date to re-create the feel of the epidural procedure.

Two basic approaches are available for generating the model: physical modeling and perceptual modeling. Whether a model is physically or perceptually based is somewhat independent of its form. For example, an equation can be a physical model or a perceptual model depending on how it was derived. The physical/perceptual distinction can also be used to judge a model independent of its derivation: does it accurately predict behavior (physics) or adequately inspire interpretation (percept)?

Physical modeling involves developing a mathematical representation based on the physics of the procedure itself. Physical modeling for an epidural simulator involves the development of a mathematical representation of the needle/tissue mechanical interaction with regard to reaction forces. Such a physical model would account for pertinent physical properties of the tissue and even tissue layering. Using this model, the simulator would derive the reaction force as a function of needle insertion depth or insertion velocity and would reflect that force to the user. In essence, a physical model would represent both the tissue and needle and predict the behavior of their interaction.

While it is reasonable to assume that a simulator which can represent the *exact* physical behavior of the needle/tissue interaction will be perceived by a user as feeling *exactly* like an epidural needle insertion, it is not necessarily the case that a simulator which *almost* behaves like a needle/tissue interaction will be perceived as feeling *almost* real. The information which is missing or distorted may be insignificant from a physical modeling perspective, but may in fact have contained the salient perceptual cues upon which a user was relying.[7] Since hardware limitations prevent even state-of-the-art force reflecting systems from perfectly representing physical interactions, it is inevitable that the physical model will not be complete. Since physical modeling provides no indication as to which information is perceptually important to the user, physical models have the potential to be inefficient or incomplete virtual representations. For example, when generating a haptic simulation of a rigid surface with a physical modeling approach, one might strive to produce an infinite stiffness spring. Since force feedback hardware cannot produce a spring of infinite stiffness, the approach may be to produce as high a stiffness as hardware will allow. A perceptual analysis of a rigid surface has revealed through human testing that the perception of encountering a rigid surface is not as strongly correlated to stiffness as it is correlated to the intensity of the initial jolt.[6,9] The indication being that an adequate perceptual model may be very different from an adequate physical model depending upon the relevant perceptual cues. Thus we can define a perceptual model of a virtual haptic sensation as one which reproduces the salient perceptual properties (i.e. the feel of the interaction) rather than representing the salient physical properties (i.e. the behavior of the interaction). Such an approach generally requires human testing to derive the required perceptual features but it has the potential of resulting in a more efficient and effective virtual representation.

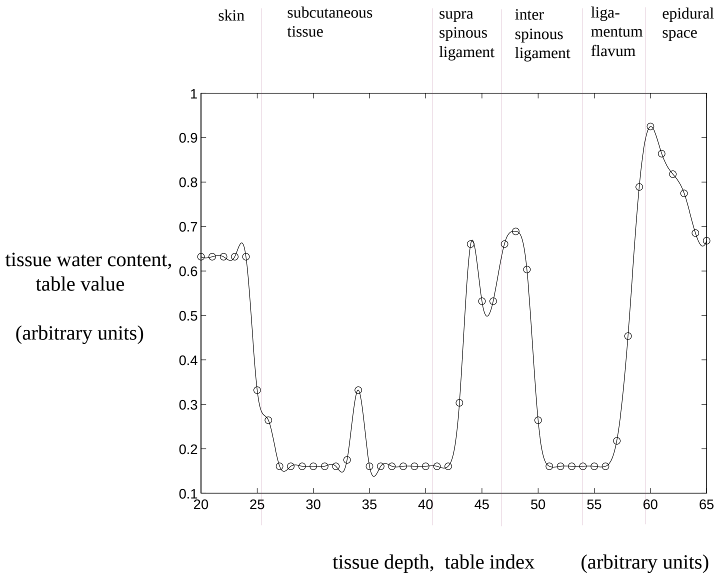


Figure 3: *CT-scan data*

Model Development

The model represents the virtual tissues; it is responsible for managing the reaction forces generated when the needle passes through the various layers of virtual tissue during the simulated epidural procedure. Two pieces of data closely associated with the epidural analgesia procedure and which are used for training purposes can provide starting points for the development of good models. One of these pieces naturally inspires a physical model and the other a perceptual model. In the following, we shall introduce both but eventually select only one as the superior basis for the model to be used in the product.

A preliminary physical model

CT-scan or MRI data of the spinal column region is readily available. CT-scans can be used to produce a volumetric representation which roughly corresponds to tissue water densities. A linear path cut through such a volumetric data set could be used to interactively report the water density of the tissue at the tip of a virtual needle as it traverses the volume under the trainee's control. Quite conceivably, such data could be used to generate the reflection forces. The assumption here, of course, is that water density provides a good direct indicator of the insertion force.

The plot in Figure 3 shows the density values at incremental locations along the insertion path as collected via CT-SCAN. A spline curve has been fit to the sampled data. Tissue layers have also been identified.

We have used this data in an interactive lookup table scheme to implement an epidural simulator. The needle position as it is read in from the encoder is used as an index to the table and the force read out of the table is commanded to the motor. The feel generated with this scheme judged by nonexperts did indeed indicate passage through layers of varying mecahnical properties. The property which varied was easily identifiable as stiffness, in particular because the force would persist even if the user stopped moving. To index the table not with position but rather with instantaneous velocity would presumably provide a better approximation to the forces reflected from insertion. An important problem, though, is that we do not have a reference or means of judging the performance of our model without a having person experienced in the epidural procedure to do the testing.

Furthermore, we hypothesize that the water density to insertion force relationship is not so simple and not direct. We assume that a tissue's water density is a simplistic and incorrect parameterization of its mechanical interaction with a needle tip. Other tissue properties such as structure, neighboring tissues, tear strength, and tissue stiffness each of which do not vary directly with water density will certainly play a role in determining needle insertion force. The physical model based on the CT-scan data was a natural first choice and perhaps a good starting point, but we want to point out that the physical parameter it reports is an incomplete picture of the physics we want to find a substitute for.

A preliminary perceptual model

A practice currently used during the initial training of anesthesiologists provides a plausible starting point for the development of a good model. Anesthesiologists in training start practicing the procedure by inserting the epidural needle through various substitute materials, usually food items. The materials chosen for training purposes are themselves data or sources of data useful for the development of perceptually valid haptic simulation algorithms.

Note that when medical instructors teach this procedure to students they do not describe the feel of the epidural insertion in terms of stiffness and density of tissue structures, but rather describe the process through perceptual analogy. For example, the feel of the needle passing through the skin is often described as puncturing the skin of a tomato. Students are even asked to practice puncturing the skin of a tomato with a needle to familiarize themselves with the haptic percept. Passing the needle through subcutaneous tissue is described as traversing the pulp of a tomato. Penetrating the supraspinous ligament feels like penetrating a ripe pear. Hitting the bone is like sticking into a cork board. Although various instructors use various perceptual analogies, the teaching technique is generally to describe the haptic landscape in terms of abstract feel parameters rather than concrete physical parameters.

The Table below lists a perceptual description of the feel of a needle penetrating each region of the insertion path as provided to us by an experienced instructor of this procedure.

Insertion through:	Feels like:
skin	puncturing the skin of a tomato
subcutaneous	traversing the pulp of a tomato
supraspinous ligamet	traversing meat of ripe pear
interspinous ligament	traversing pulp of tomato
ligamentum flavum	traversing meat of ripe pear
epidural space	exiting ripe pear
bone	hitting a cork board with a dart

We have characterized the feel of needle insertion into tomatoes and pears using the force and displacement sensored needle. Figure 4 shows the force readings as a function of needle insertion depth for a layered set of pear and tomato slices. The outer tomato slice had an intact skin in place. The force profile of the pear is visibly different from the force profile of the tomato as seen in Figure 4. The higher forces in the first 5 mm of tomato are due to the tomato skin.

We have also used this data in lookup table scheme. In order to create the lookup table, the data of figure 4 was resampled to a function, filtered, and scaled. Figure 5 shows a plot of the resulting profile which can now be used as a lookup table.

Figure 6 shows the output force as recorded by the force sensor during a needle insertion through the virtual pear/tomato slices rendered with the lookup table of Figure 5.

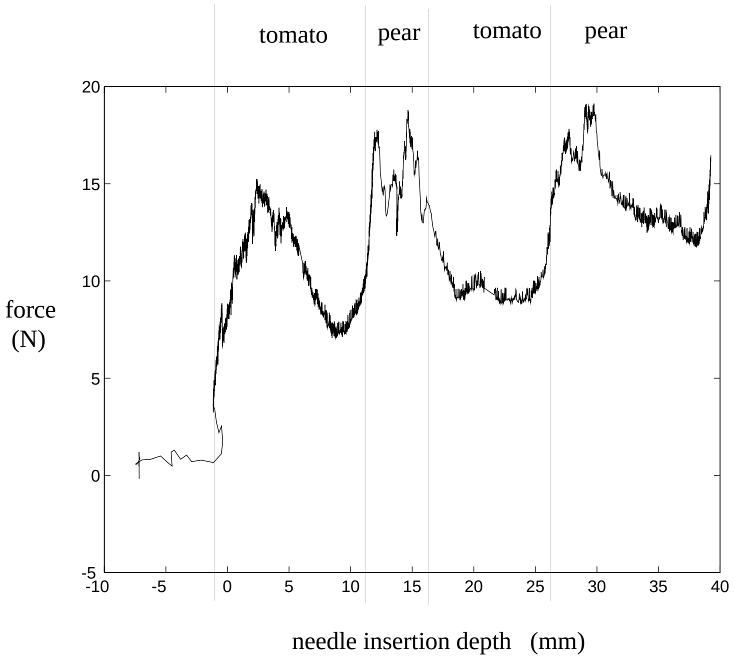


Figure 4: *Force/displacement Measurements of Real Layered Tomato and Pear Slices*

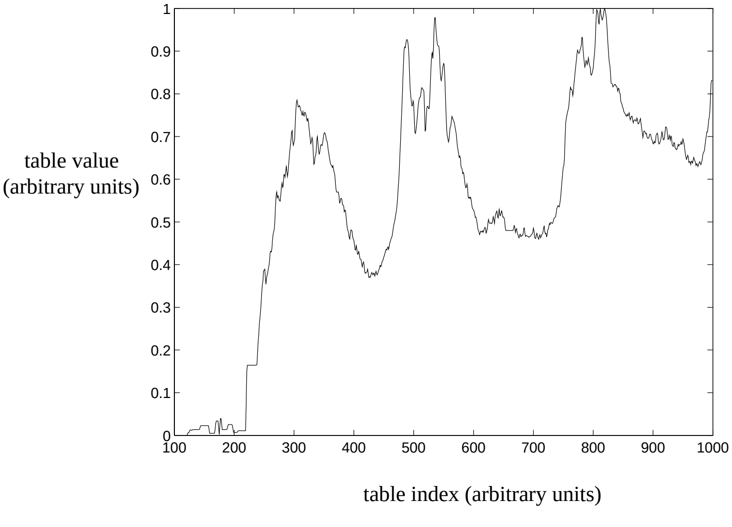


Figure 5: *Layered Pear and Tomato Profile: Lookup Table for Simulation*

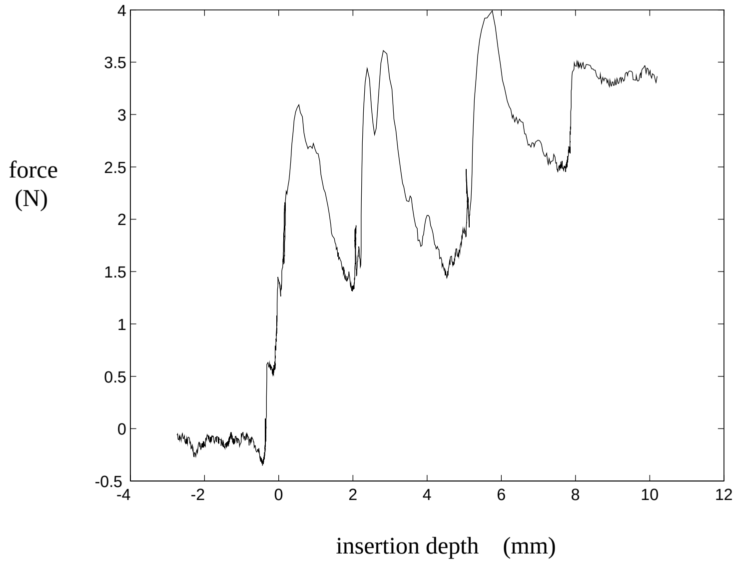


Figure 6: *Force/displacement Measurement of Virtual Layered Pear and Tomato Slices*

Note first that the forces generated in the simulation, Figure 6 are scaled down significantly from the forces measured for generation of the lookup table, Figure 4. This is due to the particular scaling chosen for the profile, and is not necessary, but does relax requirements on the simulator. The shape of the simulated force profile is indeed very similar to the shape for the lookup table. The motions made by the user during simulation were similar to the motions made during the recording of Figure 4, that is, the same insertion velocities were used. Had this not been the case, the virtual and real force profiles would have differed a great deal more. Such is the shortcoming of this lookup table approach. This can only be viewed as a first-cut simulation attempt. Once again, the forces felt were spring forces rather than damping forces since position not velocity was used to index the table.

An enhanced model

As noted above, the use of table look-up for the control law is not able to produce a truly interactive simulation. A more complete mechanical model is needed: one that represents the driving-point impedance of the handle during needle interaction with tissue. Input to such a model would include velocity and perhaps acceleration of the handle in the user's grip as well as position. An impedance characterization of the needle/tissue mechanics similar to the kind of modeling of the impedance of the human hand underway at Harvard[3] would provide models useable for fully interactive simulation. A characterization of the needle's insertion through human tissue will indeed be a part of this project. Data will be collected from a cadaver with an instrumented needle by medical instructors. But even before such models are available, we see promise in perceptual modeling. We are building models (control laws) which on the surface appear to be physical models, but which are in fact perceptual models. The basic form contains spring and damping terms. But instead of basing the parameter values on tissue characterization experiments, we are selecting them by trial and error with human subjects comparing the virtual feel to the actual feel of needle insertion into pears and tomatoes. A Windows environment supports real-time adjustment of the feel-governing parameters by the subjects. Figure 7 shows a typical dialog box with sliders for run-time parameter adjustment. To simulate layered materials of varying mechanical properties, there are multiple control laws. Each control law and its associated dialog box has a region of applicability or a pertinent range of insertion depth which can also be edited during run-time. By asking subjects, we can come up with model parameters which minimize the distance between the feel of the virtual and real tissues. Alternatively, the fit parameter could be closeness of the force measurements made during interaction with virtual tissue and

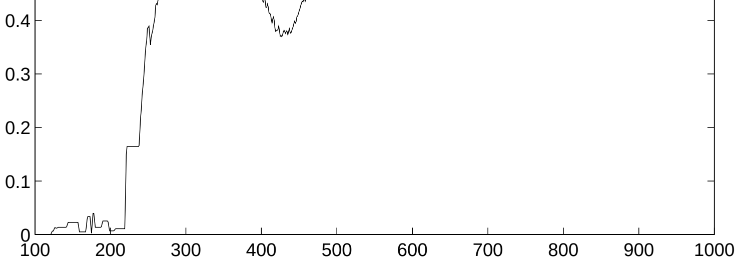


Figure 7: *Dialog Box*

sample tissue.

Other aspects of the insertion feel besides its springiness and damping which would be worthy of modeling have been suggested by this heuristic approach. The graininess of the pear, for example, appears to be an extractable perceptual feature. Sharpness of the layer interfaces is another. We are experimenting with various ad-hoc control algorithms aimed at simulating individual features which can be overlaid or added to pre-existing models. We foresee work along the lines of that of Rosenberg and Adlestein[6] which would decompose the perception of the needle/tissue interaction into a number of separable (not necessarily independent) percepts.

Finally, the model can be can be further enhanced with information available from CT-scan. The model can draw its topological or geometrical description from the CT-scan data yet keep its lumped parameter and overlaid feature form of the perceptual model described above. The variations seen from patient to patient which are available from the CT-scan would be a very valuable addition. The tissues would each be identified and their geometrical form maintained, but the simulation of their interaction with a needle would be governed by other models.

Summary

A number of models have been presented each of which might form the basis of an epidural analgesia simulator. Data from a force sensor and from the reports of users has been useful for the generation of models and criticism of models. Since our aim is to inspire perceptions in the users of the epidural simulator product, and also because adequate physical models are as yet unavailable, perceptual modeling has come to the fore as the primary model development tool.

Acknowledgements

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