

Virtual Reality Training Simulation for Palpation of Subsurface Tumors

Michael Dinsmore¹, Noshir Langrana¹, Grigore Burdea², Jumoke Ladeji³

¹ Mechanical and Aerospace Engineering

² Electrical and Computer Engineering

³ Biomedical Engineering

Human-Machine Interface Laboratory

Rutgers, The State University of New Jersey

P. O. Box 909, Piscataway, NJ 08855

Abstract

In the area of medical education, there is a strong need for palpation training to address the specific need of detecting subsurface tumors. A virtual reality training simulation was created to address this need. Utilizing the Rutgers Master II force feedback system, the simulation allows the user to perform a patient examination and palpate (touch) the patient's virtual liver to search for hard regions beneath the surface. When the user's fingertips pass over a "tumor," experimentally determined force/deflection curves are used to give the user the feeling of an object beneath the surface. A graphical user interface was developed to facilitate navigation as well as provide a training quiz. The trainee is asked to identify the location and relative hardness of tumors, and performance is evaluated in terms of positional and diagnosis errors.

1. Introduction

The use of virtual reality in surgery impacts a number of distinct areas. These include anatomy and pathology training, surgical procedure training for new surgeons, surgical planning of complex procedures, medical visualization, navigational and informational aids during surgery, predicting the outcomes of surgical procedures, and rehabilitation [2, 17, 6, 19].

The sense of touch can be extremely valuable to the trained physician when diagnosing illnesses. In the area of education, there is a need for palpation training [15]. With a combination of technologies, such as VR and force feedback, it is possible to greatly extend the capabilities and effectiveness of training simulators [1]. A simulation can record kinematics, touch, and force feedback for later display to a trainee. In this manner the trainee can learn the

methodology of a procedure, as well as experience the forces that will be encountered when performing that procedure. This technology could be used to train medical students before they palpate a real patient, and could also be used by trained physicians to improve their skill [9].

For example, while pyloric tumors in infants are palpable preoperatively in 80 percent of cases, feeling the tumor is a task which may test the patience and skill of even experienced clinicians. Medical imaging is helpful, but there is an increased reliance on these diagnostic images, leading to a decline in clinical skill in palpation of the pylorus. With appropriate palpation training, diagnosis could be made on clinical grounds alone in about 80 percent of the cases, reducing cost and diagnostic delays [14].

The current focus in our research is to integrate image segmentation, virtual reality, and force feedback technology. The overall system schematic is shown in Figure 1 [10].

This paper focuses on the development of a virtual reality training simulation where the user can touch soft tissue looking for a tumor beneath the surface. When it is touched, the tumor causes a different force profile, making it feel as though something is actually beneath the surface. If this capability were combined with medical imaging, the physician would be able to touch and examine organs that were not previously palpable without surgery [12].

The advantages of this combination extend to the classroom, where medical students could train for an examination with no risk. Currently, the way students learn these procedures is by watching experienced surgeons and performing the procedure under their supervision. If the students could be trained ahead of time to know what a tissue feels like when something is not "normal," they would gain experience prior to work on actual patients.

This paper describes the groundwork for development of a clinically viable and realistic palpation trainer for lesions. The hardware used to design this simulation is described in section 2, including 3D tracking and force feedback. Sec-

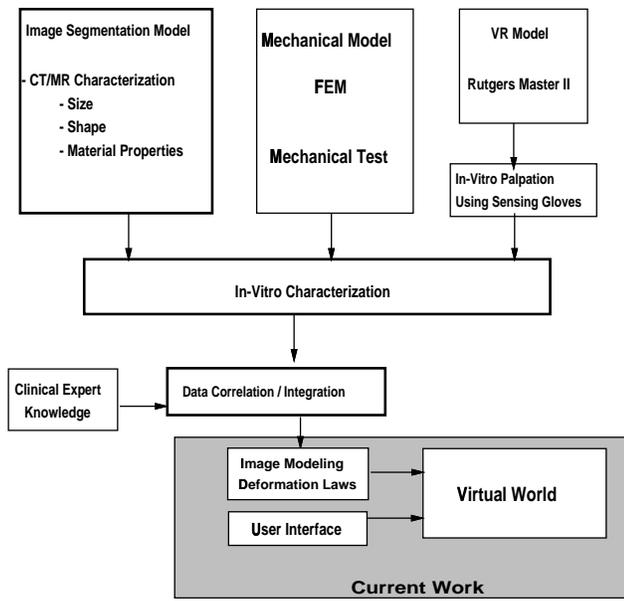


Figure 1. Model for Medical Training Simulation [10]

tion 3 discusses the issues encountered in the development of the training simulation, and section 4 details its operational characteristics and training evaluation interface. Section 5 discusses the results of an initial human factor study of the system. The paper concludes with section 6 where future work is discussed.

2. Simulation Hardware

Simulated organs need to look realistic and feel realistic when palpated. The cornerstone of our research is the Rutgers Master II (RM-II), a dextrous, portable master for VR simulations [7]. This is a light, sensorized structure (about 100 grams) attached to a standard glove. The master consists of a small, palm-mounted platform serving as the base for custom pneumatic pistons extending to each fingertip. A Polhemus FASTRAK 3D tracker provides absolute (world) coordinates of the base of the user's hand. The user wears this glove and there are no hindrances to the arm and torso. The RM-II does not prevent movement with respect to the user's upper body. The relative fingertip positions computed by the RM-II can then be converted to absolute fingertip positions for use in contact detection and deformation routines. Because the hand master is not connected to a desktop base, forces are relative to the user's palm.

A new smart interface has been developed for the RM-II [16]. It is an embedded PC controller, enabling the RM-II interface to handle the haptics loop independent of the graphics station to which it is connected. The advantage to

this control method is that the graphics station can refresh the display as fast as possible and provide force feedback information by issuing simple macro commands to the RM II through a serial port. Commands as basic as index finger is over a tumor' are now possible, thereby speeding the simulation graphics by reducing the physical modeling computational load. The current system utilizes a Silicon Graphics Indigo2 Impact workstation, capable of displaying 384,000 Gouraud shaded polygons. Code developed on this system uses the OpenGL graphics library. In the architecture shown in Figure 2, the SGI machine handles collision detection and deformation calculations along with graphics display. The RM-II Smart Interface System reads finger position input and performs force feedback calculations and control.

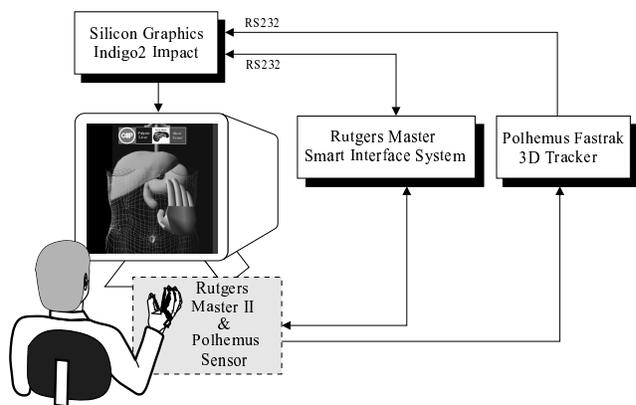


Figure 2. Current VR System Architecture

3. Development of the Simulation

To simulate the feel of regular surfaces, such as walls, the exact force response of the material is often not necessary [18]. However, when training for a specific task such as finding an embedded tumor in soft tissue, real force/deflection curves are needed so that the correct amount of force feedback is given to the users fingers.

Simulation speed becomes a very important issue when training applications are designed. On one extreme is total graphic realism, where computationally intensive ray-tracing methods can be used for photo-realism. These methods create impressive results, but may take hours to render a single frame. On the other extreme is complete real-time interaction, where delays and latencies caused by computations are unnoticeable. We see the latter extreme exhibited in video games where graphic realism is often lessened to make the game interaction "instantaneous". Training applications must exist between the two extremes, having sufficient graphic detail to accurately portray the situation, while keeping interaction as close to real-time as possible.

As described in [4], simulation speed was increased by distributing certain aspects of the code to lessen the load on the graphics workstation. The tasks of reading the position of the users fingers and outputting force to the glove were delegated to the RM-II Smart Interface System [16]. This makes the force feedback loop self contained, so that low level calculations are handled locally by the force feedback interface, and force is displayed without burdening the graphics workstation.

A high resolution model of the female body was purchased from Viewpoint Data Labs [20]. While the capability to display the torso, head, legs, and arms in great detail was desirable for our simulation, the size of the total dataset (60,000 polygons) was making the simulation refresh rate too low to be usable. Even with the contact detection and deformation routines streamlined, the rendering speed was still not at an acceptable level.

Because the trainee is only interested in the examination of the abdominal area, the size of the remaining model was reduced. First, all areas of the body not in the current field of view are not displayed. This is facilitated by segmenting the body into smaller sections ahead of time, so that portions can be selected or omitted as required. It was determined that the torso was the only segment of the body essential for liver palpation simulation. Code was developed to extract the torso vertices from the dataset. This model was usable, but was still too large for a real time simulation. Above the chest and below the waist, we use a much lower resolution draped sheet that follows the contour of the replaced sections. These routines give the realistic effect of a draped patient, while reducing the number of polygons in the model from 60,000 down to only 2,630.

To simulate a medical palpation, the code had to be expanded to handle the deformation caused by multiple fingers contacting a surface at the same time. The proof of concept for the contact and deformation routines had been previously developed for a knee palpation [11], which allowed the user to touch and feel parts of a virtual knee joint. That simulation calculated the position of the index fingertip, so it was straightforward to optimize and expand these routines to compute the positions of the middle and ring fingertips as well. Because the contact detection and deformation routines were designed to handle one point of contact and compute the corresponding deformation, calls to these functions could be repeated with the coordinates of the other fingertips. After optimization of these routines, multiple finger deformation was achieved with the loss of only a few frames per second in the graphics refresh rate.

Calculating the reaction force that is caused by a single point of deformation is relatively straightforward. The deformation distance is known and the force/deflection curve of the material is also known at that point, so the force generated can be computed as the value of the curve at the given

deflection. As multiple deformation points are considered, the calculation becomes more complex. If two points are deforming a surface, the problem arises of how to divide the reaction force between the two points. The force applied by the user is not known, only the deformation. One of the fingers could be holding the surface down while the other barely presses, or they could be pressing with equal force, or anywhere in between.

The deformation information alone is not sufficient to resolve this ambiguity. To calculate forces, we assume that the contact points are far enough apart that the force exerted by each of the fingertips has no effect on its neighbors. The reaction force for each fingertip is calculated individually, and depends only on the tissue directly beneath. If it is over the tumor, the force for that finger will be computed using the force/deflection curve for an object beneath the surface. If only soft tissue is beneath, the uniform material curve is used. In this way, the tumor location can be assessed as each finger moves over it.

To obtain realistic curves for our simulation, phantom models of hard rubber balls within larger and softer rubber balls were constructed. These phantoms were then tested under controlled conditions in order to obtain insight into the more complex medical palpations [5]. As shown in Figure 3 [3], the curves deviate noticeably with the presence of a harder inner object. The experimentally determined curves were incorporated into the liver model to indicate the existence of internal tumors. To validate the pinch testing experimental findings, FEA simulation was performed [8]. The results verified that the amount of force feedback was heavily dependent on the presence of the tumor beneath the surface.

The setting for the simulation was chosen to be an examination table in a physician's office. This environment was developed from scratch and allows for customized texture mapping of the walls and table to make the environment as familiar as possible. Framed pictures can be placed on walls as well to increase the realism of the setting.

Three dimensional anatomical datasets of a female patient and a human liver were obtained as described above to provide shell models for graphical display [20]. These datasets were then modified by other routines to make them interactive and deformable [11]. The surfaces of these models could be touched and pushed, rather than just visually examined.

4. Training Simulation

This section describes the interactive simulation, combining the research presented in the previous sections to form a basic training system for liver palpation [10]. The system allows the user to become familiar with the abdominal area by touching a virtual patient on an examination ta-

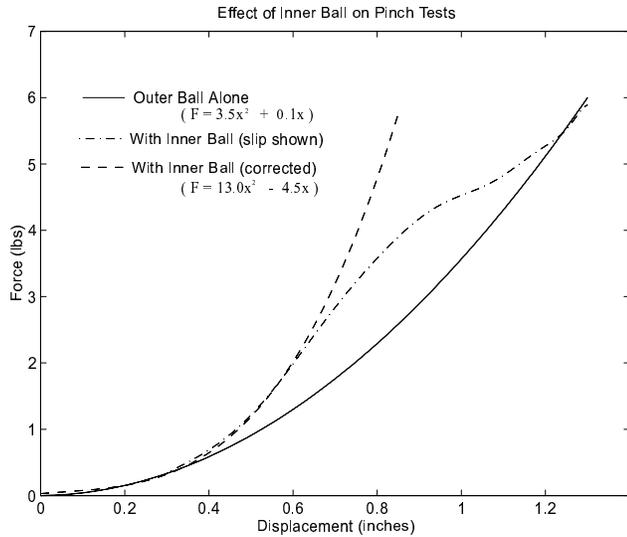


Figure 3. Experimentally Determined Force/Deflection Curves [3]

ble, and feeling a harder surface when the ribs and pelvis are touched. A graphical button interface allows the user to go inside the model and touch the liver directly, searching for harder tumors beneath its surface. Forces encountered are based on experimental testing results as previously discussed.

The user controls a virtual hand that corresponds to the orientation and finger posture of his own hand. Using this graphical hand, the user can then touch the patient's abdomen as shown in Figure 4, feeling realistic reaction forces through the RM-II, and viewing realistic tissue deformation.

The simulation takes full advantage of the capabilities of virtual reality since it allows the user to see through the patient's skin to view internal organs. A graphical toggle button is provided at the top of the screen to make the patient's skin transparent so that the liver and the digestive tract become visible to the examiner (Figure 5). The rib cage is not rendered in order not to occlude the trainee's line of sight.

Our simulation also has the capability to move the user to a viewpoint with a better view of the internal organs. A button is provided on the graphical tool bar for this purpose and when it is pressed, the viewpoint sweeps to a top view of the abdominal cavity where the liver is more easily seen (Figure 6).

From this viewpoint, the user has more options. A computer movie can be viewed showing a short 3D clip of a tumorous liver CT scan developed at Johns Hopkins University. Other buttons are provided on the tool bar to allow the user to palpate the liver if desired. When in palpation mode, the user's hand is constrained to the surface of the liver, making palpation easier. The user can touch with any finger and



Figure 4. Abdominal palpation

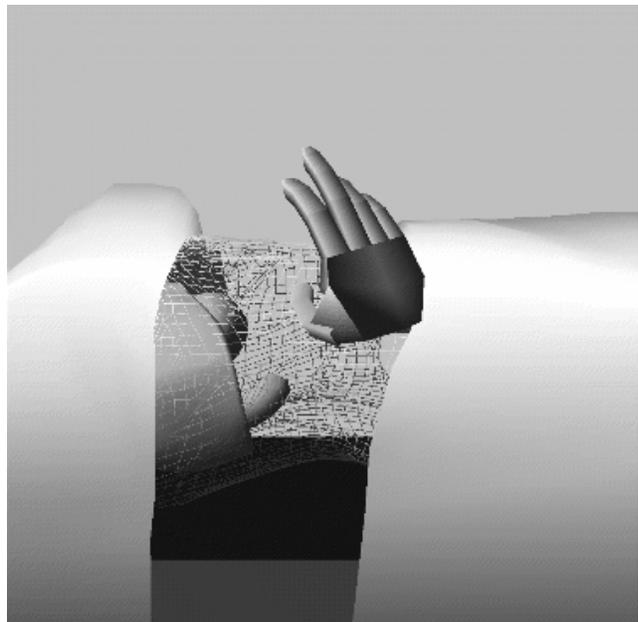


Figure 5. Transparent abdomen

feel realistic forces based on our experimental testing. If any of the fingers pass over a "tumor," the force profile under that finger changes to give the feel of an object beneath the surface.

Internal tumor phantoms are placed randomly inside the liver model for training. When passing over these sites, the user will feel either a hard or a soft tumor. When the liver



Figure 6. Viewing the internal organs

examination has been completed, the user can go back to unconstrained motion and take a short quiz about the location and hardness of the tumors. The answers are then evaluated and the trainee's performance is rated.

To train a physician in the skill of liver palpation, the simulation creates up to two tumors randomly located beneath the liver surface. Their hardness is also randomly assigned as either "hard" or "soft" to signify the type of tumor. After the liver has been evaluated, the user is given a short quiz to determine the accuracy of the examination. The user is required to identify the location and hardness (hard/soft) of any identified tumors.

The quiz takes a graphical form, where the user enters the diagnosis by moving the tip of the index finger to the suspected location and pressing 'h' or 's' to signify that the located tumor is thought to be hard or soft. A graphical marker is then displayed above the desired location, its color signifying the user's diagnosis of tumor hardness. Once all diagnoses have been entered, they are evaluated based on the actual tumor locations and hardnesses, and a report of the user's performance is printed. This report lists any tumors that were not identified, the accuracy of the specified locations, and whether or not each tumor's hardness was identified correctly. The display of the liver changes to a transparent model and the actual locations and hardnesses of the tumors are revealed as shown in Figure 7.

For training purposes, it is necessary to have the capability to save the user's actions and play them back later for evaluation. To save a user's actions, a data file was created where all inputs from the I/O devices could be stored. In a

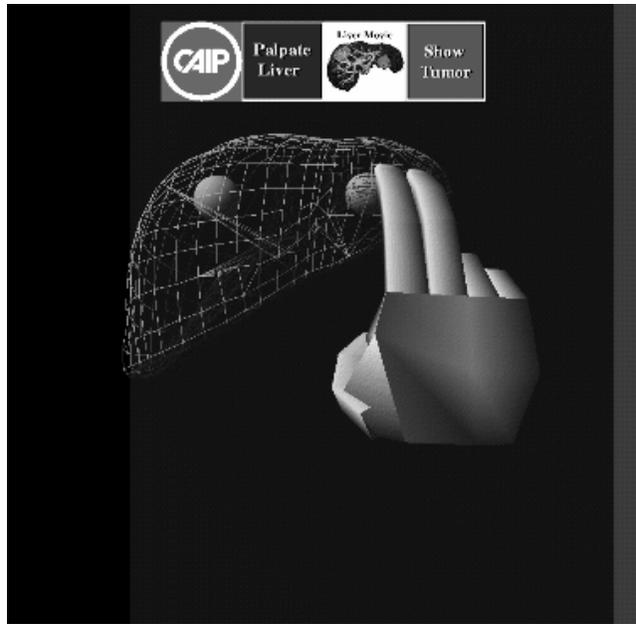


Figure 7. Liver tumors revealed

live simulation, the input for the hand on the screen is coming from external devices such as the 3D tracker for hand position, and the RM-II for finger position. To replay the user's actions, the data from these sensors was stored in a data file. For playback, the input for the simulation is read from the data file rather than from the live sensors. The simulation runs as if the data were live, and the contact detection and deformation routines are unaffected.

5. Human Factor Study

The goal of the study was to evaluate the usefulness of the virtual liver palpation simulation. The user's ability to localize and differentiate between hard and soft tumors was investigated. The effect of length of training time on the user's performance was also measured.

This preliminary study consisted of 32 subjects divided into two groups of 16. Each group had an equal number of males and females. Each participant was given an overview of the experiment and an explanation of how to obtain feedback using the RM-II. The user was then shown a scene with two balls. The red ball represented the compliance of a harder tumor while the green ball represented the compliance of a softer tumor. The background represented the compliance of the liver without any tumor. The control group (C) was given 90 seconds to become familiar with the compliance of the balls and background while the training group (T) was given 300 seconds.

Each user was then presented with six consecutive liver cases in which there was either one tumor or none. If the

user located a tumor, they then had to determine if the tumor was hard or soft as illustrated by the balls in the first scene. All the participants were presented the same cases in the same order. Two cases had a hard tumor, two cases had a soft tumor and two cases had no tumor. The following data was measured for each user

- The length of time to make a diagnosis;
- The compliance of the identified tumors;
- The location of the identified tumor.

The significance of the difference between the means of both groups was analyzed using analysis of variance (ANOVA) [13]. The results are summarized below.

There was no difference in the average time to make a diagnosis between the control group (58.6 ± 27.1 seconds) and the training group (61.5 ± 27.5 seconds), $p < 0.77$.

As stated above, there were two soft and two hard tumors for the user to identify. The difference between the average number of soft tumors correctly identified (1.00 ± 0.52) and hard tumors identified (1.44 ± 0.63) within the control group was statistically significant, $p < 0.04$. The difference in identification of soft (1.19 ± 0.75) and hard (1.5 ± 0.52) tumors correctly was not as statistically significant within the training group, $p < 0.18$. However, there was no significant difference between the ability of the control and training groups to identify soft ($C=1.00 \pm 0.52$, $T=1.19 \pm 0.75$, $p < 0.42$) or hard ($C = 1.44 \pm 0.63$, $T = 1.50 \pm 0.52$, $p < 0.76$) tumors. These results are summarized in Table 1.

	Control(C)	Training(T)
Soft Tumor	1.00 ± 0.52	1.19 ± 0.75
Hard Tumor	1.44 ± 0.63	1.50 ± 0.52

Table 1. Number of Tumors Identified

Of the four cases with tumors, the control group located an average of 3.69 tumors while the training group located an average of 3.88 tumors ($p < 0.21$). Of the tumors found, the control group correctly identified the hardness of the tumor an average of 2.44 ± 0.51 times while the training group was correct 2.69 ± 0.87 times ($p < 0.33$)

There was no significant difference in the positional errors along the x-axis ($C=0.52 \pm 0.29$ in., $T=0.47 \pm 0.27$ in., $p < 0.6371$) or along the y-axis ($C=0.37 \pm 0.17$ in., $T=0.38 \pm 0.27$ in., $p < 0.87$).

There was no statistically different result for the male versus female in any of the categories.

The results of the study indicate the following

- Both the control and training groups required approximately the same amount of time to make a diagnosis. Of the six cases presented, the initial cases tended to

take longer to diagnose than the later cases. This can be attributed to learning.

- Within each group, the participants were more likely to correctly identify a hard tumor than a soft tumor since the difference in compliance between the liver tissue and the tumors is greater for the hard tumor. In comparison to the training group, the control group identified a similar number of soft tumors. This result was the same for the identification of hard tumors.
- Even though this was a first encounter with virtual reality, the users were able to find most of the tumors. Some of the users did not locate a given tumor because a thorough search of the liver was not conducted. Thus, the system proved easy to use.
- For most of the measured variables, the control and training groups had similar results. This may mean that either the task was not hard enough or the task was so hard that the users required more or different training.
- Since some of the users also indicated that their earlier diagnoses may have been incorrect, it may be of interest to measure the effects of several training sessions. It may also be helpful to the user to have the balls representing soft and hard tumors available during diagnosis.

6. Summary

- This initial research represents a proof of the concept that computer graphics can be combined with force feedback to create a realistic and robust training system for medical palpation skills.
- The simulation goes beyond giving simple pulses or kicks when a surface is contacted. All forces felt during the simulation are calculated from engineering techniques, whether they come from simple spring models of the surface or from careful experimental testing of phantom models. Analytical techniques such as finite element modeling (FEM) have been performed off line to determine exactly how much force should be encountered in a certain situation. This has reduced the need for experimental testing of phantom models.
- The human factor study indicates there was no difference between the ability of the control and training groups to locate tumors within the simulation. The study results imply that the user can readily identify tumors with little training, but differentiating the type of tumor (soft or hard) requires additional training time.

- This simulation allows the user to interact with the anatomy to touch and learn about how certain situations will feel when they are encountered in a future examination.
- This system has the potential to be expanded to a larger and more detailed anatomical model. Because the entire body model exists, the user could choose from a library of medical procedures for training. Procedures such as breast cancer examinations would be a logical next step using this technology.

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Corresponding Author

Noshir A. Langrana,
Rutgers, The State University of New Jersey,
Department of Mechanical & Aerospace Engineering,
P. O. Box 909,
Piscataway, NJ 08855
langrana@caip.rutgers.edu

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