



PII: S0097-8493(97)00021-6

Haptic Displays in Virtual Environments

HUMAN PERFORMANCE USING VIRTUAL REALITY
TUMOR PALPATION SIMULATIONNOSHIR LANGRANA^{1†}, GRIGORE BURDEA^{2†}, JUMOKE LADEJI³ and
MICHAEL DINSMORE¹¹Department of Mechanical and Aerospace Engineering, CAIP Center, Rutgers, The State University of
New Jersey, Piscataway, NJ 08855, U.S.A.*e-mail:* langrana@caip.rutgers.edu²Department of Electrical and Computer Engineering, CAIP Center, Rutgers, The State
University of New Jersey, Piscataway, NJ 08855, U.S.A.³Department of Biomedical Engineering, CAIP Center, Rutgers, The
State University of New Jersey, Piscataway, NJ 08855, U.S.A.

Abstract Medical education has a strong need for palpation training in the detection of 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 trainee 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. The results of this training simulation are in agreement with biomechanical analysis. © 1997 Elsevier Science Ltd

1. INTRODUCTION

The sense of touch through palpation has been an extremely valuable tool since ancient times. With advances in medical imaging, there is an increased reliance on these diagnostic images, leading to a decline in clinical palpation skills in the US. In the area of education, there is therefore a need for palpation training [1]. It is also known that pyloric tumors in infants are palpable preoperatively in 80% of cases, but feeling the tumor requires patience and skill even for experienced clinicians. With appropriate palpation training, diagnosis could be made on clinical grounds alone in about 80% of the cases, reducing cost and diagnostic delays [2].

Malignant liver neoplasms far outnumber their benign counterparts. Liver cancer is more common in Asia and Africa than in the United States [3]. In the US, hepatocellular carcinoma is associated with cirrhosis in 50–80% of patients. Liver neoplasms can range in size from millimeters up to 20 cm. In the presence of cancer, the liver is generally tender to palpation. Liver tumors can be detected using imaging techniques or by palpation.

With a combination of technologies, such as virtual reality (VR) and force feedback, it is possible to greatly extend the capabilities and effectiveness of training simulators [4]. A simulation can record

kinematics, touch, and force feedback sensation for later display to a trainee. In this manner the trainee can learn the methodology of a procedure, as well as experience contact force sensation similar to those encountered when performing that clinical palpation. This technology could be used by medical students before they palpate a real patient, and by trained physicians to improve their skill [5].

The advantages of VR technology extend to the classroom, where medical students could be trained for an examination with no risk to the patient. 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.

The current focus in our research is to develop medical training tools by integrating a VR anatomical model with its biomechanical characteristics (see Fig. 1). This article 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 hidden 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 [7].

[†] Authors for correspondence.

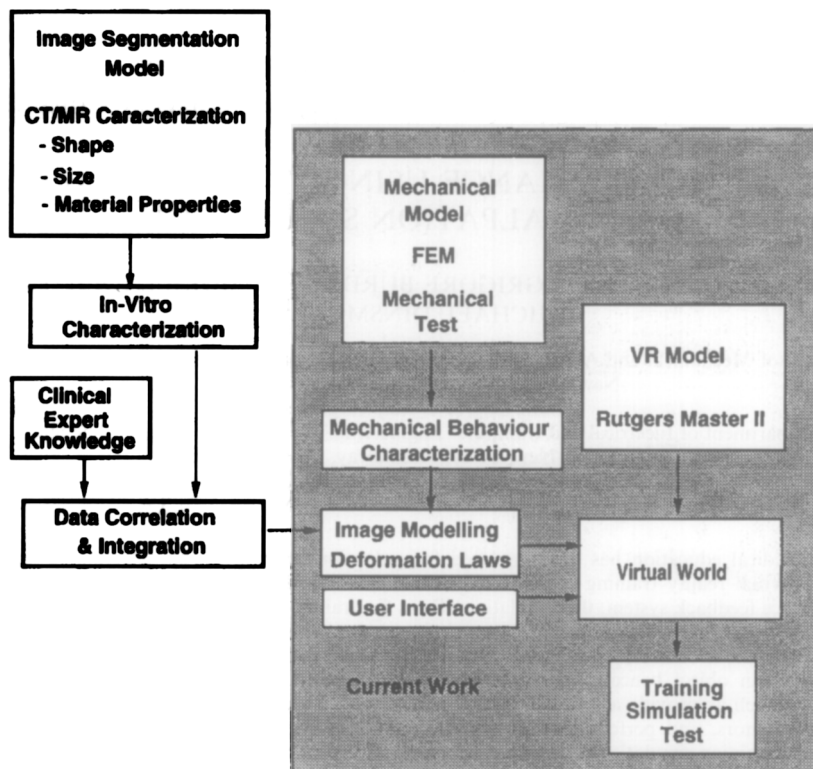


Fig. 1. Liver Training Simulation (adapted from [6]. © 1996 ASME Reprinted by permission).

2. EXPERIMENTAL CONFIGURATION

The Rutgers Master II, a dextrous, portable master for VR simulations is used to provide force feedback to four fingers [8]. The master consists of custom pneumatic actuators (pistons) extending from a palm-mounted platform to the fingertips. The high dynamic range of the RM-II coupled with large sustained force feedback levels (16N/fingertip) make it ideal as a palpation tool when fingertips are used. The RM-II does not constrain hand or arm movement, nor does it tire the user due to excessive weight. World coordinates are provided by a Polhemus FASTRAK 3D [9] mounted on the back of the palm.

The RM-II is connected to an electronics interface which displays feedback forces visually through LEDs on its front panel. This 'smart' interface includes a μ PC controller which enables the handling of the haptics loop independent of the graphics workstation [10, 11]. Force feedback information for physical modeling (such as contact detection or organ compliance) is communicated by the graphics machine to the RM-II interface via a serial line. Thus the graphics computer computation load is reduced, resulting in higher refresh rates. The graphics workstation used in our simulation is an SGI Indigo2 High Impact capable of rendering 384 000 Gouraud shaded polygons per second. The simulation was developed using the OpenGL graphics library [12].

The SGI workstation handles collision detection, deformation calculations, and graphics display (Fig. 2). The RM-II Smart Interface reads the hand configuration and then calculates and controls force feedback to the trainee's hand.

3. BIOMECHANICAL MODELS

In order to develop a realistic virtual simulation, there is an acute need to have deformation laws in multi-material property structures. These laws can be obtained from mechanical models which will simulate the contact force (at the finger tips with and without a glove) vs deflection behavior (of the tissue configuration). Here we would like to know how different tissues will deform locally under the finger tips. This behavior is dependent on many factors such as the type of tissue (normal, soft, hard, firm and cyst), tumor location (at the surface or deep), their mechanical properties and mechanical properties of the surrounding tissues, boundary conditions (firmly or loosely attached), and the finger tip palpation forces (magnitude, direction and locations).

Initial studies [12, 14] indicate that deformation under the finger tip is sensitive to the material properties and location of the hard tissue within the soft tissue. Therefore, a major task here is to quantify and simulate the deformation of the normal soft tissue with tumor underneath. These structures

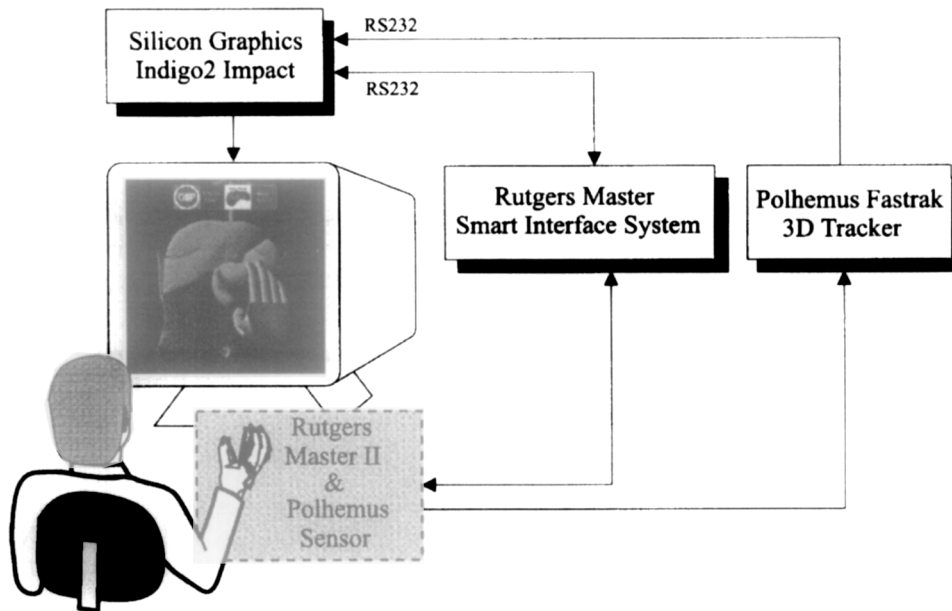


Fig. 2. Current VR system architecture (adapted from [13]. © 1997 IEEE Reprinted by permission).

are considered a multi-material model from a finite element analysis point of view. A finite element model was developed to introduce a realistic scenario of the size of the tumor and its location within the surrounding soft tissue.

3.1. A parametric study on the location of tumor

The phantom model (Fig. 3) is a two dimensional model in the direction of the loads and passing through the center of a circular tumor. The soft

tissue takes the majority of the area in the model, and the hard tissue is considered as the round area with a radius of 20 mm. This tumor size is chosen based on the data reported in the literature [3, 15]. A parametric study was performed where the distance between the surface of the hard tissue and the surface of the soft tissue varied from 25% to 200% of the hard tissue radius. The stiffness, E , of the soft tissue was 137 MPa while the stiffness of the hard tissue varied from 10% to 600% of the soft tissue stiffness.

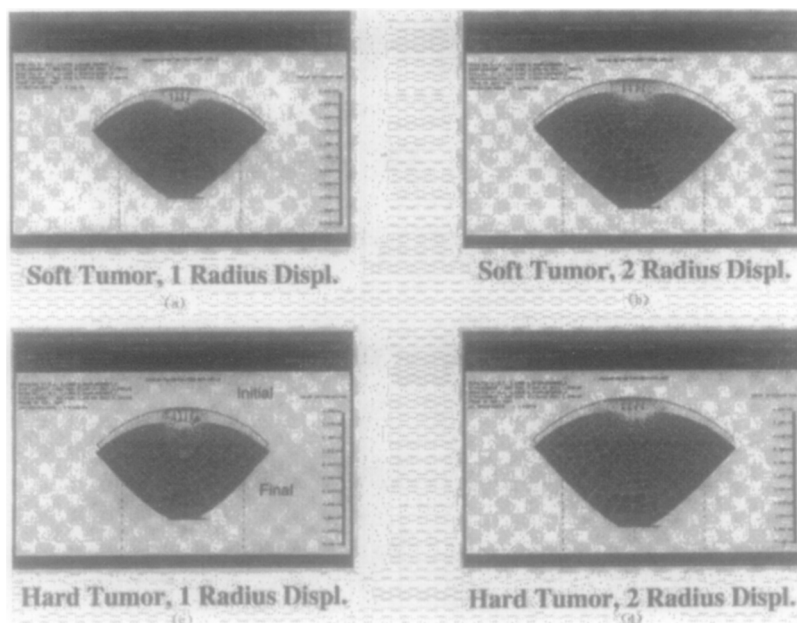


Fig. 3. Finite element analysis on hard and soft tumors [7].

Each load was 20 N vertically on the surface. The effect of the force is local in all cases, uniform all across except where the finger is pushing, and the lower portion of the model has almost no deformation. The boundary of the tumor may change depending on its relative stiffness.

—For one-finger palpation on the surface of the soft tissue with embedded tumor softer than the surrounding tissue, the following results were found:

- The finger sinks in more (or larger deformation) as the tumor itself deforms significantly [Fig. 3(a); the maximum deformation is 2.03 mm].
- The sinking effect decreases dramatically as the tumor gets deeper, and shows insignificant alteration once the tumor is deeper than one and half times its radius [Fig. 3(b); the maximum deformation is 1.79 mm]. This deformation is similar to a normal case.
- The surface deformation in case (a) was 39% higher compared to case (b).

—For one-finger palpation on the surface of the soft tissue with embedded tumor harder than the surrounding tissue, the following results were found:

- the sinking effect was much smaller as the tumor did not deform. The majority of the deformation was in the soft tissue. The tumor was simply displaced [Fig. 3(c); the maximum deformation is 1.32 mm].
- As the distance increased, the effect of the hard tumor decreased dramatically [Fig. 3(d);

the maximum deformation is 1.37 mm]. Once the location of the tumor was deeper than 1.5 times the radius, the results were similar to soft tumor. This implies that tumors deeper than 1.5 times their radius are very difficult to palpate.

- The results of the multiple finger palpation loads show that the finger pressing directly on top of the tumor has maximum force feedback.

4. TUMOR DETECTION SIMULATION

A real-time simulation for liver palpation training that incorporates force feedback has been developed [13]. A high resolution model of the female body was obtained from Viewpoint Data Labs [16]. This model was subsequently reduced from 60 000 polygons down to 2630 polygons by displaying only the region of interest (from the fifth rib to the waist) in high resolution. The rest of the torso was draped with a virtual sheet. The details of the simulation are shown in [12] and [13].

Multiple finger contact detection and deformation was achieved by extending the routines developed earlier in our laboratory for knee palpation [17]. The reaction force due to deformation at a point was obtained from experimentally measured force/deflection curves. A tumor embedded in soft tissue was simulated *in vitro* using hard rubber balls embedded within softer balls. These experiments were validated using FEA as discussed above. The reaction force for each fingertip was computed individually. This assumes no interaction between the forces exerted by each finger.

The simulation allowed the trainee to palpate,

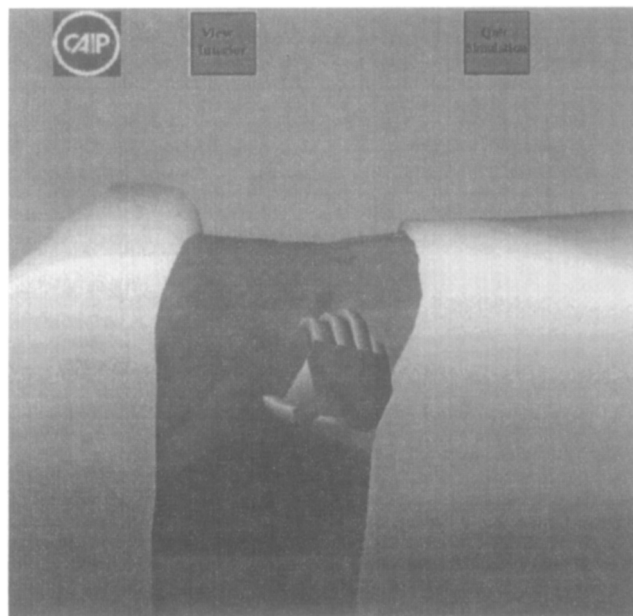


Fig. 4. Abdominal palpation (adapted from [13]. © 1997 IEEE Reprinted by permission).

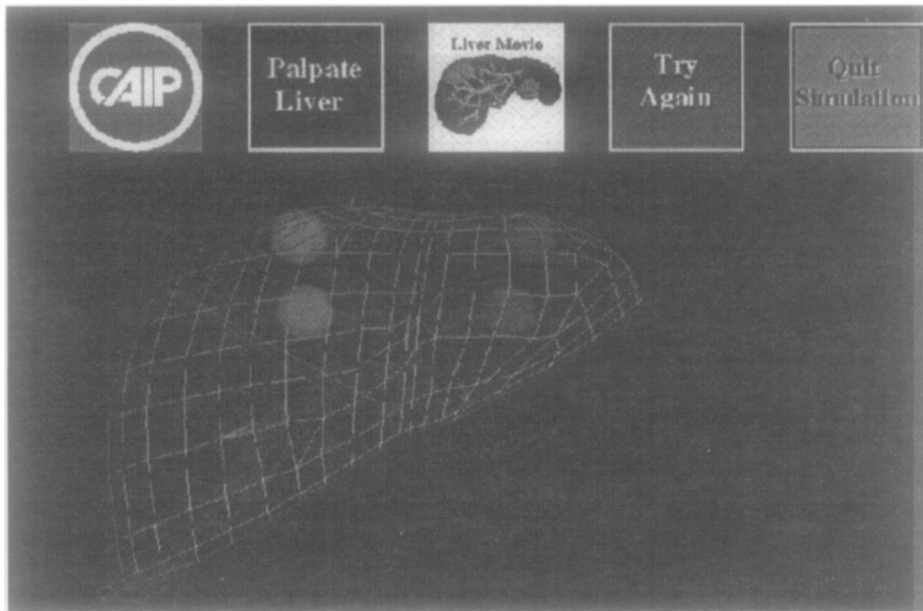


Fig. 5. Feedback to user on tumor identification. In this figure, the user is shown the potential error along the x-axis. The top row of tumors represent the user's identification of tumor compliance and position.

using three fingers, the ribs and other areas of the abdomen (Fig. 4). The user can then choose to palpate the liver directly. In the palpation mode, the trainee's hand is visually constrained to the surface of the liver. On palpation, the user feels a constant compliance due to the liver tissue deformation. When the finger is placed over an area in which a tumor was embedded, the area has a higher reaction force (feels less compliant). The compliance of soft and hard tumor phantoms were modeled.

In the simulation, the tumors were placed randomly by the computer. The trainee had to identify a tumor as hard ('h'), or soft ('s'), when it is encountered. He then received feedback on the correctness of the diagnosis and the error between the position of the detected and actual tumors (Figs 5 and 6). The trainee was subsequently shown any tumors he had been unable to detect.

5. HUMAN FACTORS STUDY

To evaluate the training simulation, a human factors study was conducted using 32 subjects. These were volunteers and non-medical students. The goal

of the study was (1) to investigate a user's ability to locate and differentiate between hard and soft 'tumors', (2) to investigate search duration, and (3) to investigate the influence of training time on the above results.

Two groups of 16 subjects each (eight males and eight females) participated in this study. The study was approved by the Institutional Review Board at Rutgers University. The subjects had little or no previous experience with the RM-II or other VR interfaces.

5.1. Experimental protocol

The first group, 'Control', was given 1.5 min to interact with two spheres that represented the compliance of hard and soft 'tumors'. The compliance of the background represented liver tissue. The second group, 'Experimental', was given five minutes to accomplish the same task. All participants were instructed to discriminate between the feedback due to hard and soft tumors. The participants were then asked to identify the hardness of a tumor, if found.

```
You have found the correct number of tumors.n (499)
You missed the left tumor by 1.13812 units.
You correctly identified the hardness of the left tumor.
You missed the right tumor by 0.475113 units.
You correctly identified the hardness of the right tumor.
```

Fig. 6. Feedback to user on tumor identification.

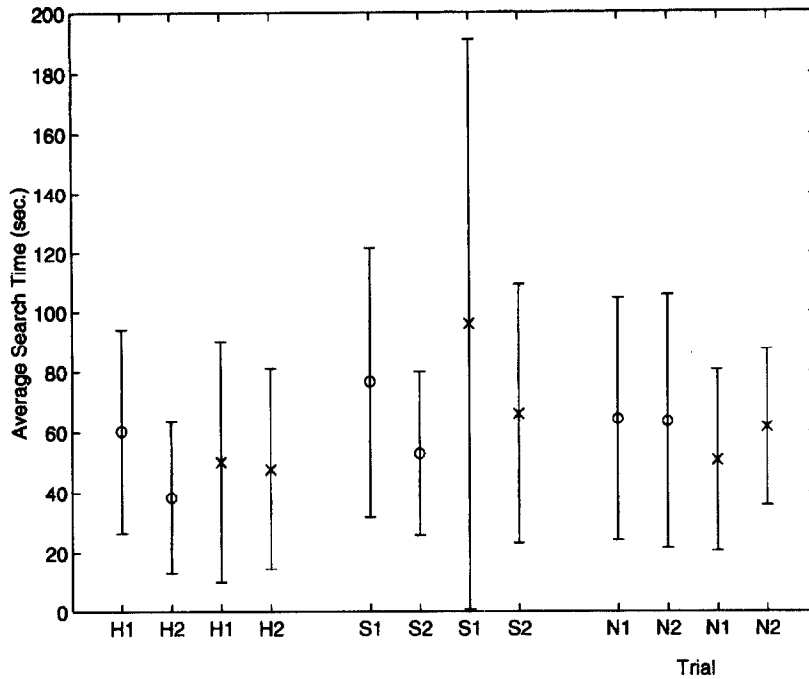


Fig. 7. Average search time. O: control, X: experimental, H1 and H2: hard tumor, S1 and S2: soft tumor, N1 and N2: no tumor.

Each subject was presented with six consecutive liver cases which contained either one tumor or no tumor. The liver cases were presented in the following sequence for all subjects; soft tumor, hard tumor, soft tumor, no tumor, hard tumor, no tumor. The subjects were not aware of this sequence. During the training period, the subjects were told to indicate their tumor location and compliance as follows. If a tumor was found, the subject was instructed to place their index finger over the tumor and press 'H' for hard tumor, or 'S' for soft based on their recollection of the training spheres. If no tumor was found, the subject was told to press 'N' on the keyboard. The significance of the difference between the means of both groups was evaluated using analysis of variance (ANOVA) [18].

5.2. Results

SEARCH TIME: The average search time for the control group (58.6 s) was not significantly different from that of the experimental group (61.5 s, $p > 0.05$). Figure 7 illustrates the average search time for each subject. The subjects in both groups required more time to locate the soft tumors than the hard tumors.

Tumor compliance: the control group found an average of 3.69 of the four tumors while the training group located and average of 3.88 ($p > 0.05$). Of the tumors found, the hardness of the tumor was correctly identified an average of 2.44 times (out of 3.69) by the control group while the training group was correct 2.69 times (out of 3.88) ($p > 0.05$).

Of the six liver cases presented to the subjects, two contained a hard tumor and two contained a soft tumor. Within the control group, significantly more hard tumors (1.44) were detected and correctly identified than soft tumors (1.00), $p < 0.04$. In the experimental group, the difference between the number of hard tumors detected and correctly identified (1.5) and the number of soft tumors identified (1.19) was not statistically significant, $p > 0.05$.

As shown in Table 1, the experimental group detected 20% more soft 'tumors' than the control group.

Positional errors: along the x -axis, the positional errors were not significantly different between the control group (1.3 cm) and the experimental group (1.12 cm), $p > 0.05$. The positional errors along the y -axis were not significantly different between the control group (0.93 cm) and experimental group (0.95 cm), $p > 0.05$. Figure 8 illustrates the Euclidean error for each tumor detected.

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

Table 1. Number of tumors identified^a

	Control	Experimental
Soft tumor	1.00±0.52	1.19±0.75
Hard tumor	1.44±0.63	1.50±0.52

^aAdapted from [3]. © 1987 IEEE Reprinted by permission.

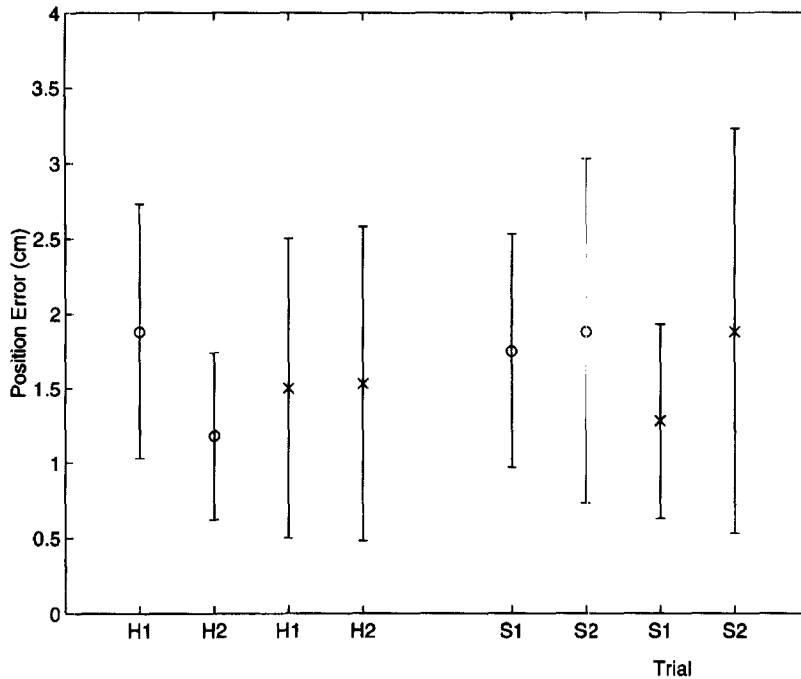


Fig. 8. Euclidean error. ○: control, ×: experimental.

5.3. Discussion

Both the experimental and control groups were able to locate almost all the tumors they were presented with. The control group located 92% of the tumors while the experimental group located 97% of the tumors. Once a tumor was located, both groups were able to correctly identify its compliance more than half of the time. The control group correctly identified the compliance of the tumors 66% of the time, while the experimental group was correct 69% of the time.

The control and experimental groups required approximately the same amount of time to make a diagnosis. Of the four tumor cases, the effect of learning was more pronounced in the control group. The learning for the experimental group may have occurred during the training period.

Since the difference in compliance between the liver tissue and the tumors is greater for the hard tumors, the participants were more likely to identify the hard tumors. This result correlates with FEA results. Furthermore, the soft tumor deforms as force is applied which makes the detection difficult. This was shown in the FEA plots.

The experimental group, which had more training in VR did better, by 20%, on the diagnosis of soft 'tumors' than the control group. The users were able to locate the tumors with minimal error even though this was their first encounter with virtual reality. The users were more likely to locate a tumor if a thorough search was conducted.

For most of the measured variables (with the exception of soft tumor detection), the control and

experimental groups obtained similar results, with the experimental group having slightly better results. This may mean that either the training methods need improvement, or that the task did not require extensive training.

6. CONCLUSIONS

These proof-of-concept research results show that VR 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 given situation. This has reduced the need for more extensive experimental testing of phantom models.

The human factors study indicates there was little 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 diseases will feel when they are encountered in a future examination. The 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. The current efforts are aimed towards development of breast self-examination (BSE) training tools. It is believed that this type of training tools should revolutionize the way training education is performed. However, careful force measurement of actual malignant tumor palpation (not phantoms) needs to be done. Finally, human factors tests need to involve medical students and input from expert physicians.

Acknowledgements—The research reported here was partially supported by the New Jersey State Commission on Cancer Research, and by the CAIP Center, Rutgers University (with funds provided by the New Jersey Commission on Science and Technology and by CAIP's industrial members). The authors would like to thank Daniel Gomez (PhD, Electrical and Computer Engineering Department), Emmanuel Pere (visiting scientist, Aerospatiale France), Eric Harper, Dave Overaker, and Wen-Chung Fen (graduate students, Mechanical and Aerospace Engineering Department) for their technical assistance.

REFERENCES

- Ota, D., Loftin, B., Saito, T., Loa, R. and Keller, J., Virtual reality in surgical education. *Computers in Biology and Medicine*, 1995, **25**, 127–137.
- Merry, C., Palpation of a pyloric tumor. *Irish Medical Journal*, 1993, **86**, 26.
- Okuda, K. and Ishak, K. D. (eds.), *Neoplasms of the Liver*. Springer-Verlag, New York, 1987.
- Burdea, G., *Force and Touch Feedback in Virtual Reality*. Wiley, New York, 1996.
- Keating, J., Matyan, T. A. and Bach, T. M., The effect of training on physical therapists' ability to apply specified forces of palpation. *Physical Therapy*, 1993, **73**, 45–53.
- Langrana, N., Burdea, G., Dinsmore, M., Gomez, D., Harper, E., Silver, D. and Mezrich, R., Virtual reality training simulation with force feedback: palpation of lesions. In *Proceedings of 1996 Advances in Bioengineering, ASME Bioengineering Symposium*, Vol. BED-33, 1996, pp. 435–436.
- Langrana, N., Burdea, G., Mezrich, R. and Dinsmore, M., *Development of training tools for palpation of lesions*. Final Report to NJ State Commission on Cancer Research, 1996.
- Gomez, D., Burdea, G. and Langrana, N. A., Integration of the Rutgers Master II in a virtual reality simulation. In *Proceedings of IEEE VRAIS '95*, 1995, pp. 198–202.
- Polhemus, *Fastrak User's Manual*, Colchester, Vermont, 1993.
- Gomez, D., A dextrous hand master with force feedback for virtual reality. PhD Thesis, Department of Electrical and Computer Engineering, Rutgers University, May 1997.
- Pere, E., Gomez, D., Burdea, G. and Langrana, N., PC-based virtual reality system with dextrous force feedback. In *Proceedings ASME Winter Annual Meeting, Atlanta, GA*, Vol. DSC-58, 1996, pp. 495–502.
- Dinsmore, M., Virtual reality simulation: training for palpation of subsurface tumors. Master's Thesis, Department of Mechanical and Aerospace Engineering, Rutgers University, October 1996.
- Dinsmore, M., Langrana, N., Burdea, G. and Ladeji, J., Virtual reality training simulation for palpation of subsurface tumors. In *Proceedings of IEEE VRAIS '97*, 1997, pp. 54–60.
- Harper, E., Dinsmore, M., Langrana, N. A. and Burdea, G., Interactive graphical models of objects with varying stiffnesses. In *Proceedings of Virtual Reality in Medicine and Developers' Expo, SIG-Advanced Applications, Inc.*, Virtual Reality Solutions, Inc., New York, 1995, 70–74.
- Mitchell, Jr., G. W. and Bassett, L. W. (eds.), *The Female Breast and Its Disorders*, Williams & Wilkins, Baltimore, MD, 1990.
- Viewpoint Data Labs International, *Viewpoint Catalog, SIGGRAPH '95 Edition*, Orem, UT, 1995.
- Langrana, N., Burdea, G., Lange, K., Gomez, D. and Deshpande, S., Dynamic force feedback in a virtual knee palpation. *Journal of Artificial Intelligence in Medicine*, 1994, **6**, 321–333.
- The Math Works, Inc., *Statistics TOOLBOX for Use with MATLAB. User's Guide*, Natick, MA, 1995.