Digital Human Modeling for Palpatory Medical Training with Haptic Feedback

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R.L. Williams II, J.N. Howell, and R.R. Conatser Jr., 2008, "Digital Human Modeling for Palpatory Medical Training with Haptic Feedback", in Handbook of Digital Human Modeling for Applied Ergonomics and Human Factors Engineering, Chapter 48, ISBN 978-0-8058-5646.

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Introduction

This chapter discusses work in palpatory diagnosis training for schools of medicine and allied health. Palpatory diagnosis involves identifying medical problems via touch. First we present a literature review to establish the state of the art in palpatory diagnosis using virtual reality and then we present a case study: The Virtual Haptic Back project at Ohio University. Haptics indicates the human sense of touch and haptic interfaces provide force and touch feedback from virtual environments. Our digital human modeling includes both realistic 3D surface models of the back geometry and accurate compliance measurement of human tissue in vivo.

Literature Review

Haptics, the science of touch, is being applied in medical virtual reality environments to increase realism and training effectiveness. In the medical field, most haptics/biomedical references relate to surgery, including suturing, endoscopy, intubation, injections, and patient rehabilitation, all of which require significant tactile skills. The Immersion Corporation (www.immersion.com) has developed haptic interfaces for injection training and sinus surgery simulation. Virtual reality (VR) with haptic feedback is also currently of interest in the dental field for simulation of drilling and of other dental procedures (e.g., Yau et al., 2006; www.sys-consulting.co.uk/web/projects/project_view.jsp?code=haptics). The remainder of this literature review will focus on a less-developed, but promising, area, applying haptics and virtual reality to non-invasive, non-surgical palpatory training for medical diagnoses.

In the Stanford Visible Female project (Heinrichs et al., 2000), a 3D stereoscopic visualization of the female pelvis has been developed from numerous slices of 2D pelvis data. Haptic feedback was enabled via the PHANToM haptic interface, allowing the user to interact with and feel the virtual model. A virtual reality-based simulator prototype for the diagnosis of prostate cancer has been developed using the PHANToM haptic interface (Burdea et al., 1999). Another tumor palpation VR simulation was developed by Langrana (1997). Crossan et al.

(2001) are using a PHANToM haptic interface in an equine ovary palpation simulator, for pregnancy determination in veterinary training. The Virtual Haptic Back is under development at Ohio University to augment the palpatory training of osteopathic medical students (Howell et al., 2006). This project has implemented a combined graphical and haptic model of a human back on a PC, using two PHANToM® 3.0 interfaces for haptic feedback.

Temkin et al. (2002) are augmenting The Visible Human Project of the National Library of Medicine with a haptic device to improve the teaching of anatomy via touch. Basdogan et al. (2001) have presented a haptic simulator for bile duct diagnosis. For actual patients with, Stalfors et al. (2001) have developed a method to model head/neck cancer conditions graphically and haptically, enabling doctors to palpate remotely, thus using telemedicine for remote diagnosis and monitoring. Riener et al. (2004) have presented a haptic knee joint simulator for clinical knee joint evaluation training. McLaughlin et al. (2004) have developed a haptic simulation of the female clinical breast examination since breast cancer is a major health problem for women in the U.S. Kevin et al. (2001) report a system wherein a pressure transducer records the real-world forces in an expert's palpatory examination of a patient's abdomen for later playback via a haptic interface in a virtual model, for student training purposes.

Case Study: The Virtual Haptic Back (VHB)

VHB Project Motivation and Overview

The initial stage of learning palpatory diagnosis is a challenge for many osteopathic medical students. The Virtual Haptic Back (VHB) is being developed as an aid in the teaching and learning of palpatory diagnosis. It simulates the contours of human backs and the compliances (reciprocal of stiffness) over their surfaces, and allows these to be felt through the haptic interfaces. Regions of abnormal tissue texture are simulated with altered surface compliance.

The Virtual Haptic Back (VHB) was initially developed for training students of osteopathic medicine, but will be applicable in related areas, such as physical medicine and rehabilitation, physical therapy, chiropractice and massage therapy. The VHB augments traditional training in the difficult art of palpatory diagnosis (identifying medical problems via touch). Via two PHANToM® 3.0 haptic interfaces, the student can explore a realistic virtual human back with accurate graphical and haptic (force and touch feedback) representations (Figure 1). Realistic somatic dysfunctions of different difficulty levels are programmed in random locations for the student to find by touch. The VHB can be used for student practice and as a repeatable, objective evaluation tool to track student progress.

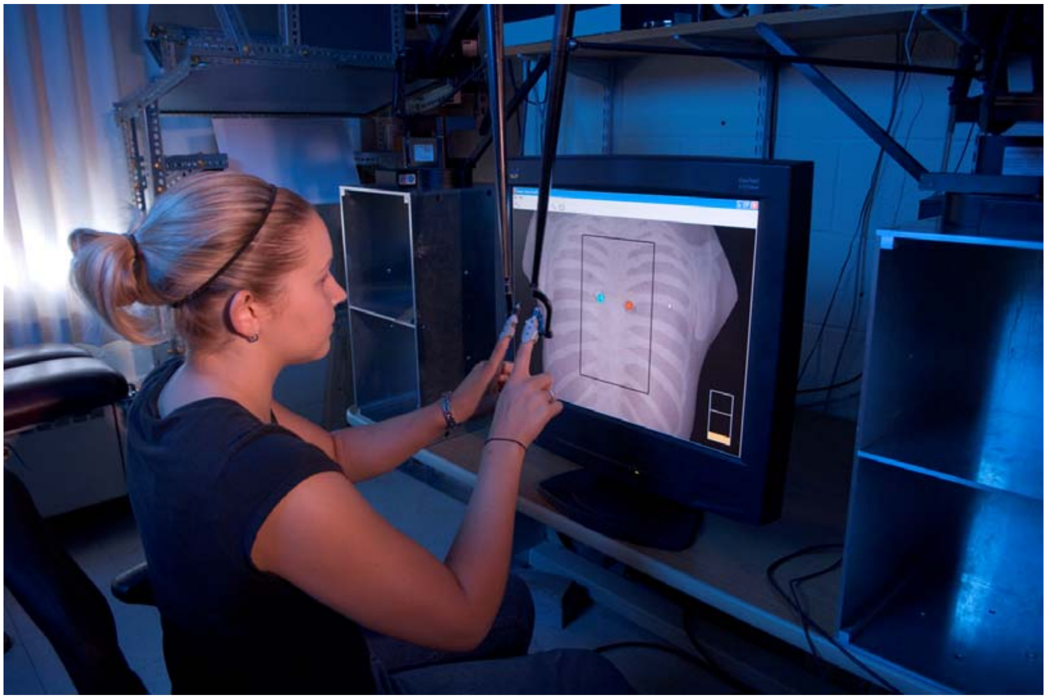

Figure 1. Medical Student Practicing Palpation with the Virtual Haptic Back

The model consists of the contour of a back plus the compliances of the surface. For the initial version the contour was modified from the Visible Female data set. Subsequent contours have been obtained from living subjects with 3D photography. The compliance values were initially chosen to match the subjective feel of a back, as determined by osteopathic specialists in manual medicine. They were spot checked against compliance measurements made on actual human backs, using the Phantom 3.0, equipped with a modified probe 2 cm in diameter, which assessed displacement as a function of force applied in graded steps up to 6 N.

VHB users feel the virtual back with two fingers (or a finger and a thumb) placed into the thimble-like receptacles at the ends of the PHANToM haptic interfaces. Behind the virtual haptic back by approximately 15 cm is a full-sized image of the back displayed on a 23 inch flat screen monitor (Figure 1). Two dots (L and R) on the screen indicate to the user visually where his/her left and right fingers are with respect to the haptic back (see Figure 2). In this way the user is able to bring his/her fingers directly to the center of the back in order to begin palpation.

In the model used for testing, the back was programmed (C++ in the General Haptic Open Software Toolkit, GHOST®SDK, with OpenGL for graphics) to have a uniform compliance except for one 2.5 by 3.0 cm region. The entire region of testing was a rectangle superimposed on the graphics image of the back 13.5 cm wide and 22 cm high; it encompassed thoracic segments T5 – T10. The compliance of the abnormal region, which ranged from 2.45 to 0.972 mm/N, was made to blend smoothly into the compliance of the surrounding areas (2.52 mm/N) with a hyperbolic tangent function. Subjects typically moved their fingers along the back searching for regional differences in feel, and then went back to explore the region or regions they suspect might be abnormal. When they had decided which area was abnormal, they pressed a foot switch. A recorded voice provided immediate feedback as to whether their choice was correct or not.

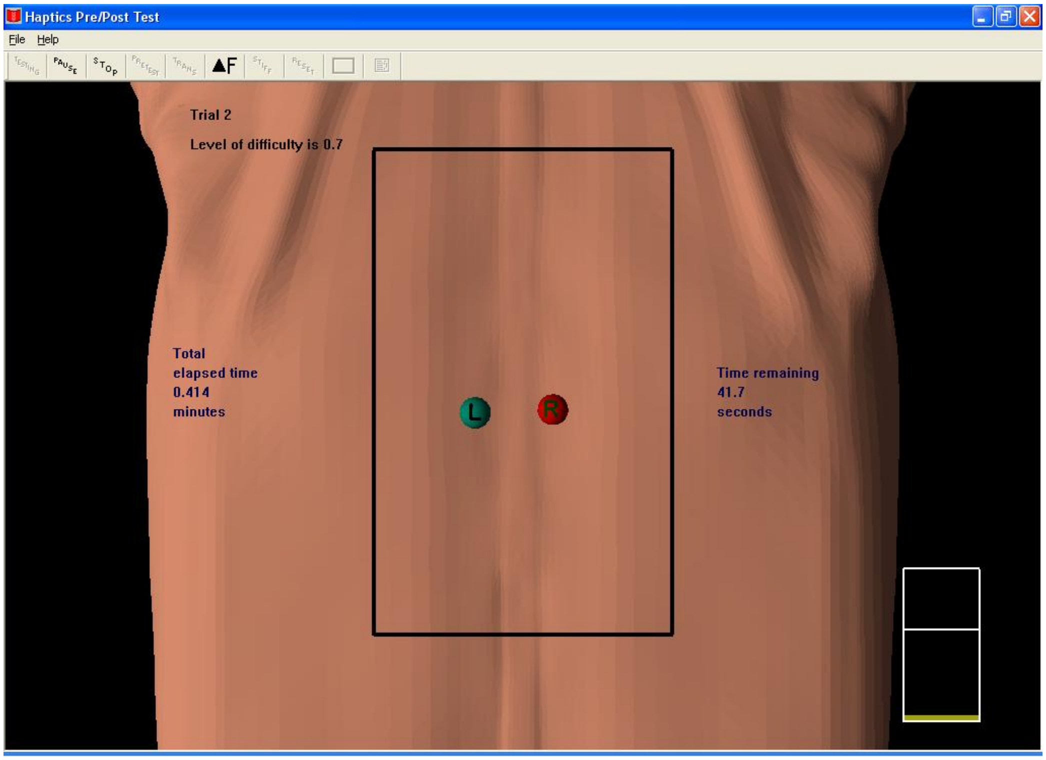

Figure 2. Graphic image of VHB during the pre- and post-tests. Dots marked L and R indicate the position of the two palpating fingers. The large rectangle indicates the region where abnormal compliance can be found. Trial number and difficulty level appear at upper left. Total time elapsed in the test appears at left; time remaining in the present trial appears at right. The box in the lower right is a force indicator which rises to the level of the horizontal line before a voice warns against using so much force.

In discriminating between two different linear compliances, applying greater force causes increasingly greater differences in displacement. This led users to press harder if they were having difficulty detecting the abnormal region. This was undesirable for two reasons. Application of force levels over 6 *N* caused the PHANToM electric motors to overheat. Second, application of high forces is inappropriate clinically, both because of potential patient discomfort and because palpatory information from superficial soft tissues can be lost by applying too much force. We did the following in order to discourage users from pushing too hard. 1. When they applied unacceptably high forces, automated voice feedback warned them not to press so hard. 2. A visual gauge in the lower right of the screen monitored their force levels, enabling users to see when they were approaching unacceptable levels. 3. More importantly, the programmed compliance difference between the abnormal area and the surrounding areas was multiplied by a hyperbolic tangent function that made the difference gradually disappear with increasing displacements between 8 and 16 *mm*. Thus the differences were maximum in a desirable range of force application, about *3 N* in the normal regions. Based on preliminary measurements, this force level falls within the range of forces typically exerted by fingers in clinical palpatory diagnosis. Figure 3 shows the compliance functions programmed.

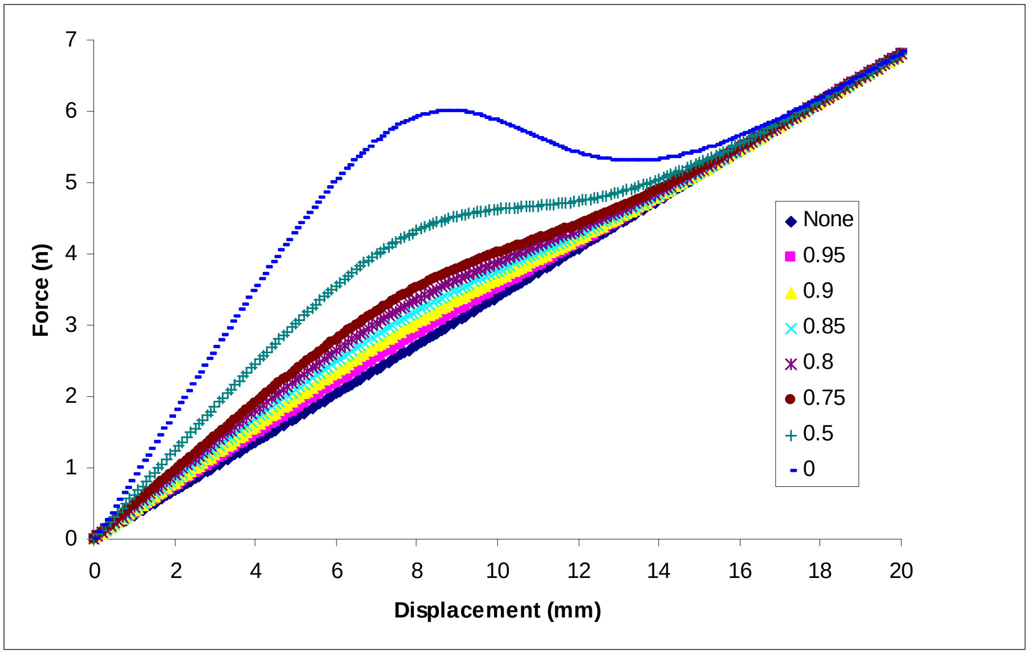

Figure 3. Relation between force and displacement at different difficulty levels. The straight line indicates background stiffness (the reciprocal of compliance). Increasing deviations from background make the task progressively easier. The deviations disappear at high displacements produced by application of high forces. The functions are implemented to simulate clinical palpatory situations.

Table I shows the range of compliance values used in the current VHB model. The Weber fraction W expressed as a percentage is defined to be:

$$W = \frac{C_b - C_x}{C_b} \times 100\%$$

where C_b = 2.52 mm/N is the background compliance used (for 'normal' back properties and C_x is the abnormal area compliance, given in the table. We assign arbitrary difficulty levels as given in Table I.

Table I. VHB Abnormal Compliance Values Used

Difficulty Level	**Compliance C_x (*mm*/*N*)**	**Weber Fraction *W* (%)**
0.00	0.97	61.5
0.25	1.19	52.8
0.50	1.51	40.1
0.70	1.98	21.4
0.75	2.14	15.1
0.80	2.25	10.7
0.85	2.29	9.1
0.90	2.35	6.7
0.95	2.45	2.8
0.99	2.50	0.8

Hardware and Software

For details regarding our VHB hardware and software, please see:

http://www.ent.ohiou.edu/~bobw/html/VHB/VHB.html

This includes information on system specifications, haptic interfaces, our 3D viewing options (Ji et al., 2006), the playback feature (Williams et al., 2004), multi-point collision detection, our 3D Camera for measuring the 3D contour of human backs, virtual motion testing (Chen et al., 2006), and our measurement of human tissue compliance in vivo (Williams et al., 2007).

Training Methods

The volunteer subjects (N = 21) were first-year osteopathic medical students within the first 3 months of their palpatory training. During their first session in the lab they were given an opportunity to familiarize themselves with the haptic interfaces, practicing 10-15 minutes identifying regions of abnormal compliance until they were comfortable with the task. During these initial familiarization sessions a transparency function was activated, permitting the user to see the skeletal elements beneath the skin (Figure 4). This feature was turned off during the pre- and post-training sessions and during the training sessions in between the tests.

The Pre- and Post-Tests

Following the practice phase subjects took a test in which they had to locate the regions of abnormal compliance presented in successive trials. The locations varied randomly between sessions. The abnormalities could be on the left or on the right and at any one of 6 vertebral levels (T5 – T10). Five different levels of difficulties, i.e., magnitude of compliance differences, were presented, starting with the easiest and progressing step-wise to the most difficult (1.51, 1.98, 2.25, 2.35 and 2.45 mm/N, compared to the background compliance of 2.52 mm/N). At each difficulty level there were two trials. Each trial was completed in 1 minute; time remaining in each was presented on the screen. Midway through the test, the program paused, giving the user an opportunity to take his/her fingers out of the apparatus and rest his/her arms, before finishing the test. This test was administered again at the end of the two-week practice sequence as a post-test in order to determine the improvement in performance resulting from the practice.

The Practice Sequence

Following the pre-test subjects carried out the first of eight practice sessions, which were completed over a 2-week period. Subjects were permitted to do the practice sessions at their own convenience, but no more than one session per day. The total time of each practice session was limited to 15 minutes. Although the default setting of the program started at the easiest level (greatest compliance difference), subjects could at any time pick any level of difficulty on which to work. Most tended to start with the easier levels and progress to the harder levels. In the practice sessions, when subjects made an incorrect diagnosis, i.e., incorrect localization, the recorded voice told them of their error and the program displayed a box around the correct area (Figure 4) on the screen with the transparency function turned on. Subjects could then go back and feel the abnormality before going on to the next trial. Subjects could also choose to pause the program at any time in order to rest their arms.

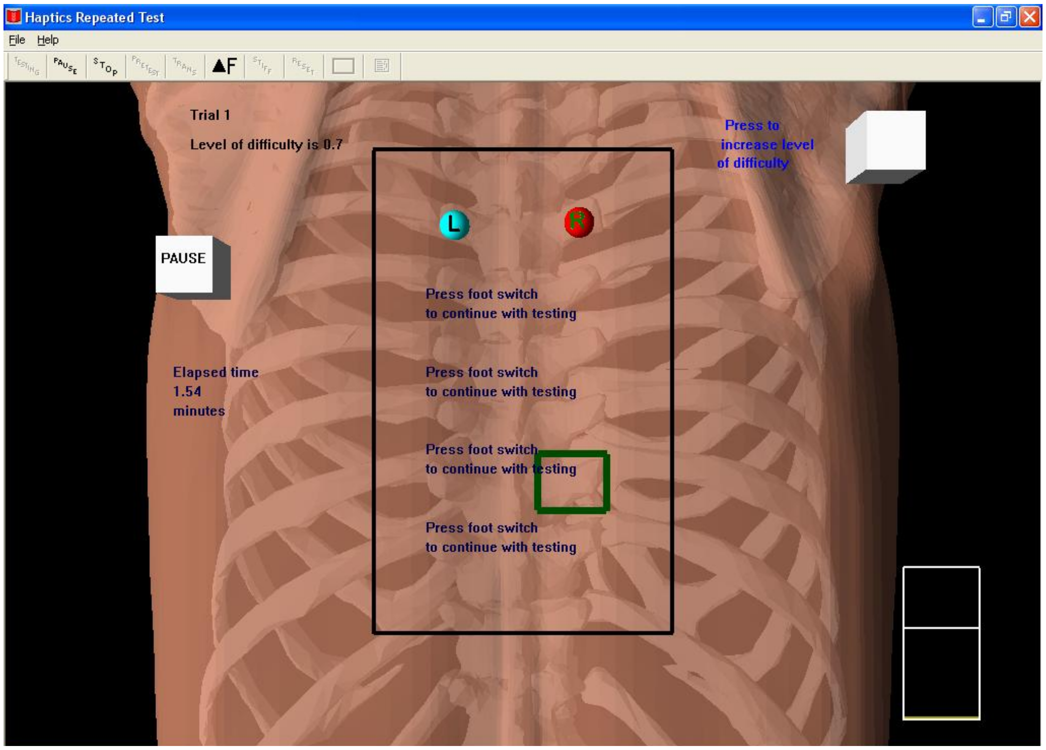

Figure 4. Appearance of the screen following a wrong answer in the practice sessions. The transparency function is activated to reveal underlying bone. The small green box indicates the actual location of the abnormal area. The user can practice palpating this area before going on to the next trial. By touching the upper left box with an L or R finger dot, the user can pause the program; by touching the upper right box the user can alter the difficulty level of the next trial. These boxes can be accessed at any time during the practice sessions.

Data Analysis

Results from the pre- and post-tests were analyzed for each difficulty level by t-test. Results from the practice sessions were analyzed by repeated measures ANOVA.

Evaluation Results

Significant differences in performance accuracy between the pre- and post-tests were seen only at difficulty levels of 0.7 and 0.8, corresponding to compliance values of 1.98 and 2.25, respectively (Figure 5). At the easiest levels performance was better than at the harder levels, especially in the pre-test. A trend toward better performance with practice at these levels might have reached statistical significance with a bigger N. Even easier levels that were included in the practice sessions were not included in the pre- and post-tests. At the harder levels performance dropped off to what are probably chance levels (see Discussion) and at these levels no significant pre- to post-practice performance differences were observed.

Performance monitored in the practice sessions revealed gradual improvement over the eight sessions revealed at difficulty levels of 0.7, 0.75, and 0.8 (compliance values of 1.98, 2.14 and 2.25, respectively). This is illustrated in Figure 6 for the difficulty level of 0.75.

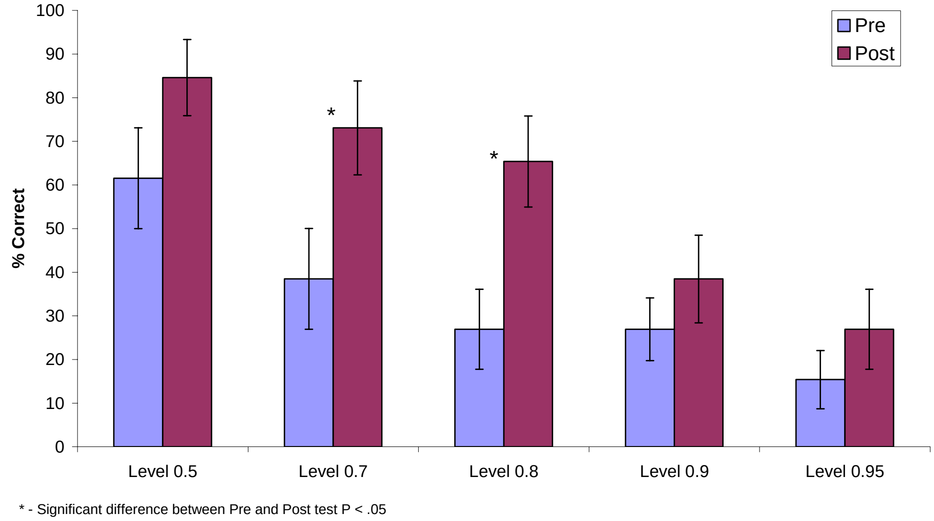

Figure 5. Comparison of percent correct responses in tests before and after the practice sessions as a function of difficulty level of the task. The difficulty levels from easiest to hardest (left to right) correspond to compliance values of 1.51, 1.98, 2.25, 2.35 and 2.45. Baseline compliance value was 2.52. In this and subsequent figures, vertical bars represent standard errors of the mean values.

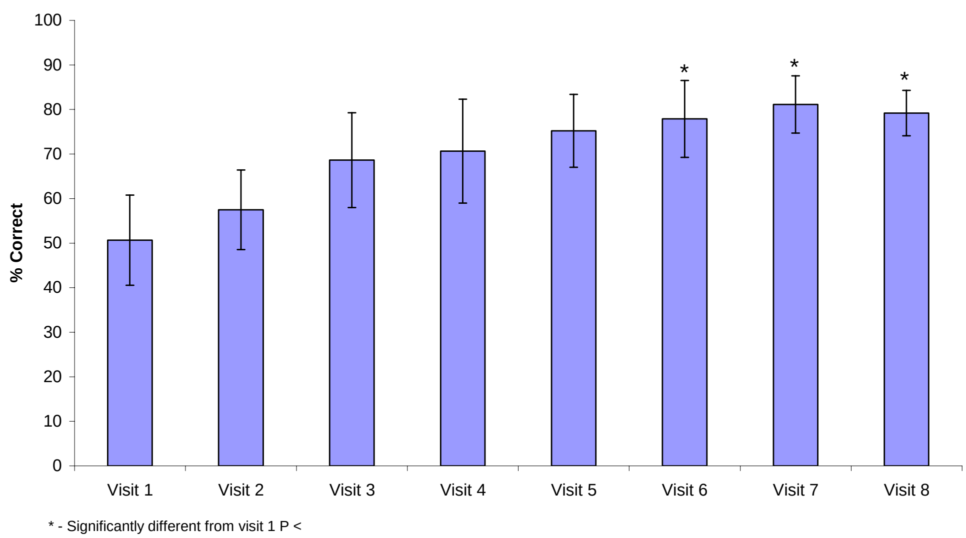

Figure 6. Percent correct localizations as a function of practice session (visit) number for difficulty level of 0.75 (compliance value of 2.14). Performance in the last three sessions was significantly ($P<0.05$) better than that in the first session.

Cumulative averaged results for all difficulty levels, all practice sessions, and all subjects are shown in the 3D plot of Figure 7. It emphasizes that performance falls off as the difficulty level rises. The rise in performance as a function of visit number is also apparent in the range of difficulties at which performance falls off. At the easiest levels, to the left, users did very well even in the first practice session. At the hardest level, at the far right, accuracy improved with successive practice sessions, but remained near chance level throughout. The most dramatic improvement is seen at intermediate levels of difficulty where users performed poorly during the first practice sessions, but progressively better in successive sessions.

Upon finishing the training and the post-test, subjects were asked three questions. The first question was “Do you think this practice with the haptic back will be of help to you in the development of your palpatory skills in OMM lab?” Of the 21 subjects, 17 marked “yes;” 4 marked “maybe;” and no one marked “no.” The second question was, “Do you think further practice with the haptic back would be of help to you in the development of your palpatory skills?” Twelve subjects answered “yes;” 8 marked “maybe;” and 1 subject marked “no.” They were also asked to rate the realism of the simulation on 0 to 10 scale, with 0 being unrealistic and 10 being very realistic. The mean value reported was 6.5.

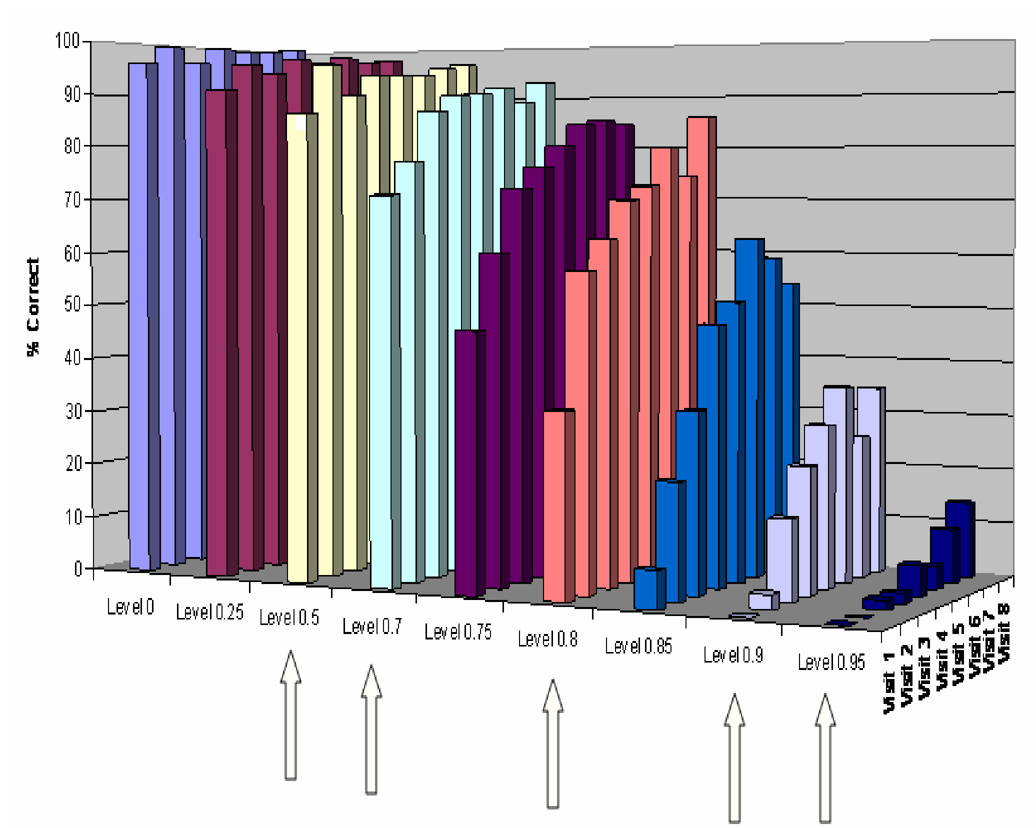

Figure 7. Percent correct localizations during practice as a function of both visit (session) number and difficulty level (designated in units of compliance). As the difficulty level increases, moving from left to right on the graphed surface, performance falls off. At the difficulty levels at which performance falls off, improvement can be seen with increasing visit number. The arrows indicate difficulty levels used in the pre- and post-tests.

Discussion

VHB capabilities and limitations. The VHB combines graphics and haptics into the simulation of the human back and is beginning to find applications as a training tool in medical education and as a research tool in the study of touch. The data presented here relates to both of these applications.

A simulation is only as good as the data upon which the simulation model is based. The intent of the VHB is to simulate the process of palpatory diagnosis in which a practitioner of manual medicine uses his/her fingers and hands to sense the mechanical properties of the patient's body surface. The VHB model, using the PHANToM, is limited in that it simulates only the gross contours and the compliance of the back normal to the surface. The haptic interfaces do not permit the user to feel fine contours detectable only by the mechanoreceptors of the skin, and the model is devoid of any thermal component. Shear forces are also currently not simulated. The force feedback provided by the haptic interfaces simulates primarily the proprioceptive component of palpation.

In principle the most accurate force feedback simulation would be based on high resolution compliance measurements over the entire surface of the back. Although current work in our laboratory is directed toward that goal, the compliance model used in this study was largely based on feedback from practicing physicians who specialize in manual medicine. This evaluation by practitioners seems vital in that, because of the incompleteness of the model with respect to sensory modalities, it is conceivable that the most perfectly simulated compliance characteristics would not provide the best simulation of the palpatory experience. Only the practitioners can tell us that, and, unless the model passes this test, it will not be accepted by them as an effective aid in teaching/learning palpatory diagnosis.

Compliance detection results. A standard measure in the analysis of sensory systems is that of the limit of detection, the just noticeable differences (JND) (Gescheider, 1997). In some sensory systems, such as auditory and visual, two questions are of interest, 1) the lowest signal level that can detected, and 2) the smallest change in signal intensity expressed as a fraction of the absolute intensity value, known as the Weber fraction. In the case of compliance detection, only the latter has meaning. Although our experimental setup was not optimally designed for the precise determination of the Weber fraction, our results do yield an average value of 11% after training.

Using a device that permitted control of the compliance and of the total displacement used in a pinching movement between the thumb and index finer, Tan et al. (1995) demonstrated that compliance detection measured against a baseline compliance of 4 mm/N averaged a Weber fraction of 8% when displacement in all trials was the same. The authors argue that under these conditions the subjects have information about the terminal force at the end of the movement and what was measured was the ability to discriminate force, rather than compliance. The similarity of their value with previously measured Weber fraction for force measurement, 7% (Pang et al. 1991) supported their argument. They then repeated the experiment, but varied the displacement randomly during the trials. Without the terminal force cues compliance detection then decreased to 22%.

Using a PHANToM 1.5 haptic interface, Dhruv and Tendick (2000) found Weber fractions in the range of 14% - 25%, depending on the baseline level of compliance against which the differences were detected. With a baseline of compliance of 8 mm/N the detection threshold was 14%, but with a baseline of compliance of 2 mm/N detection threshold was 25%. A subsequent study with the PHANToM yielded a detection threshold of 8-12% (De Gersem et al, 2003, cited in De Gersem et al, 2005).

The classical method of determining the Weber fraction, done in these studies, presents the subject sequentially two surfaces, objects or situations. The subject indicates which has the higher compliance. This is repeated many times. Since there are two choices only, chance score is 50%. Typically the threshold value for detection is taken as 75% - halfway between chance and completely reliable detection. In our study the chance value was somewhere between 8.3% and 16.7%, depending on whether or not the user was touching one or two back regions when s/he depressed the foot switch. This is consistent with performance at the hardest level in the pre- and post tests (Figure 5). Taking 20% as chances level, 60% correct identifications would then be halfway between chance and 100%. A mean of 60% was achieved in the pre-test at a difficulty level of 0.5, which corresponds to a Weber fraction of 40%. In the post-test, subjects achieved 60% correct at a difficulty level of 0.8. This corresponds to a Weber fraction of 11%. This figure agrees well with the Weber fraction of 8-12% reported by De Gersem et al. (2003).

The improvement in the Weber fraction from 40% to 11% between pre- and post- tests may overestimate the training effect somewhat, in that part of the learning may really represent familiarization with the haptic apparatus. This is suggested by the fact that performance improved significantly between the pre-test and the first practice test session. At the 0.7 difficulty level pre-test performance was about 35% while performance during the first practice session at that difficulty level was already 70%, similar to the post-test value (Figure 5). The gradual improvement in performance seen at somewhat harder levels of difficulty, 0.75 (Figure 6) and 0.80 (not shown) suggests that, in addition to the rapid learning from familiarization, a slower learning process also took place.

Further work will be necessary to determine what the limits are of learning in this context and what the absolute physiological limits of compliance detection might be. It will be interesting to see if, through more extensive practice than used in this study, the Weber fraction can be brought down to that of the force detection results reported by others in the literature.

Clinical palpatory diagnosis training undoubtedly involves improvement in both the ability to feel small compliance differences and in the ability to impart meaning to what is felt. The improvement in performance with practice on the VHB is likely to reflect primarily the former, but the complexity and realism of the model may require some of the latter. Strong positive feedback from medical student subjects suggests that experience with the VHB may be also helpful in both of these aspects.

The data discussed was collected for N=21 medical students during Winter 2006. In Fall 2006 we improved the realism of our model and the precision of our training protocol and repeated the study with the entire in-coming class of first-year medical students at Ohio University. Data from 89 students were included in the study. These data, as yet unpublished, indicate the same trends as shown in the study with the 21 volunteer subjects discussed in this chapter, with regard to improvement in accuracy (Weber fraction) and speed with practice on the VHB.

Summary

We presented a literature review detailing the state-of-the-art in palpatory diagnosis training with virtual environments and haptics augmentation. This area requires digital human modeling in 3D surface models and tissue compliance. We then presented a case study of the VHB, a haptic simulation of human back for medical and related palpatory diagnosis training. We used the VHB to assess the limit of human compliance detection and to explore the effects of training. Compliance detection values obtained are similar to those reported by other investigators and an eight-session training period over two weeks significantly improves performance.

Acknowledgements

The authors gratefully acknowledge grant funding from the Osteopathic Heritage Foundation of Columbus Ohio for supporting this work. We also thank members of the Virtual Haptic Back Team and Interdisciplinary Institute for Neuromusculoskeletal Research for project work. We acknowledge expert palpatory physicians David Eland, D.O., and Janet Burns, D.O. The authors thank David Noyes for hardware construction and intellectual contributions.

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