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The Virtual Haptic Back: Detection of Compliance Differences

John N. Howell, Robert L. Williams, II, Janet M. Burns, David C. Eland, Robert Conatser
Interdisciplinary Institute for Neuromusculoskeletal Research, Ohio University, 210 Irvine Hall, Athens, OH 45701, USA

ABSTRACT

The ability of human subjects to distinguish small compliance differences in adjacent regions was tested with the Virtual Haptic Back (VHB), a simulation of human backs designed to aid in teaching medical palpatory diagnosis. The VHB uses two PHANToM 3.0 haptic interfaces (SensAble Technologies, Inc.). The contours and compliance properties of the backs are represented graphically and haptically. Medical students practiced 8 times over 2 weeks on the VHB, finding regions of altered compliance, the locations of which varied randomly. Baseline compliance was 2.52 mm/N; compliance in the abnormal regions ranged from 2.45 to 0.97 mm/N. Following the practice session the threshold of detection is 2.25 mm/N, an 11% difference from baseline.

INTRODUCTION

The Virtual Haptic Back is being developed as an aid in the teaching of medical palpatory diagnosis (Howell et al., 2005). Palpation of the human back is used diagnostically by osteopathic physicians and others to detect musculoskeletal abnormalities collectively referred to as somatic dysfunction. These abnormalities include altered tissue texture, which reflects altered tension in underlying muscles and other tissues. A major component of tissue texture is tissue compliance, displacement per unit of applied force (the reciprocal of stiffness). The VHB simulates the contour and compliance properties of human backs, which are palpated with two haptic interfaces (SensAble Technologies, Phantom 3.0), permitting simultaneous palpation with two fingers. Students can practice detecting and localizing compliance patterns that reflect clinically observed abnormalities.

In this study we used the VHB to estimate the limit of detection of compliance differences, i.e., the just noticeable differences (JND) in compliance detectable by users prior to and after eight practice sessions. When the JND is expressed as a fractional change it is known as the Weber fraction (Gescheider, 1997). Jones and Hunter (1990) reported a Weber fraction of 0.23 for compliance differences detected by movement at the elbow joint. Using a compressive movement between the thumb and index finger, Tan et al. (1995) reported a mean Weber fraction of 0.22 that varied with the range of movement permitted during the test. It ranged from about 0.18 with a range of motion of 3.5 cm to about 0.38 with motion restricted to 1.5 cm. Dhruv and Tendick (2000), using a PHANToM 1.5 haptic interface, found Weber fractions in the range of 0.14 – 0.25 for a finger pressing against a resistance behaving as a linear spring. Weber fraction values obtained depended on the range of compliances examined, being 0.14 with a mean compliance level of 8 mm/N and 0.25 with a mean compliance level of 2 mm/N.

Because we are developing the VHB as a training tool for the rather difficult task of clinical palpatory diagnosis, we need to demonstrate that there is a transfer of skill between the VHB and actual clinical palpation. Osteopathic medical students are typically trained in palpatory diagnosis and manipulative treatment over two years, during which time it is thought that their palpatory skills improve. The present study was undertaken to determine if practice on the VHB results in improved palpatory performance on the VHB. The data permit us to estimate the Weber fraction for the detection of compliance by a cohort of osteopathic medical students in the context of simulated palpatory diagnosis on a virtual human back. Following two weeks of training medical student subjects achieved a JND of 0.11, measured with compliance values in the range of 2.52 to 0.97 mm/N.

METHODS

THE VHB MODEL

The model consists of the contour of a back plus the compliances of the surface. The contour was modified from the Visible Female data set. The compliance values were initially chosen to match the subjective feel of a back, as determined by osteopathic specialists in neuromusculoskeletal 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, from the same or different hands, placed into the thimble-like receptacles at the ends of the PHANToMs. 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 visually where the user's fingers are with respect to the haptic back. In this way the user is able to bring his/her fingers directly to the center of the back in order to begin palpation.

Figure 1. Graphic image of VHB during the pre- and post-tests. Dots marked L and R indicate the position of the two palpating fingers. The 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 too much force.

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.

$$F(x) = \tfrac{1}{2}[\tanh(a[x-b]+c) - \tanh(a[x-b]-c)]$$

Where a is the distance over which compliance transitions, b is the distance between the center of the abnormal area and a reference point, such as the body midline, and c is the width of the abnormal area. 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 suspected 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.

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 electric motors of the PHANToM 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 the forbidden zone. 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 (Figure 2). Based on preliminary measurements, this force level falls within the range of forces typically exerted by fingers in clinical palpatory diagnosis of superficial soft tissues.

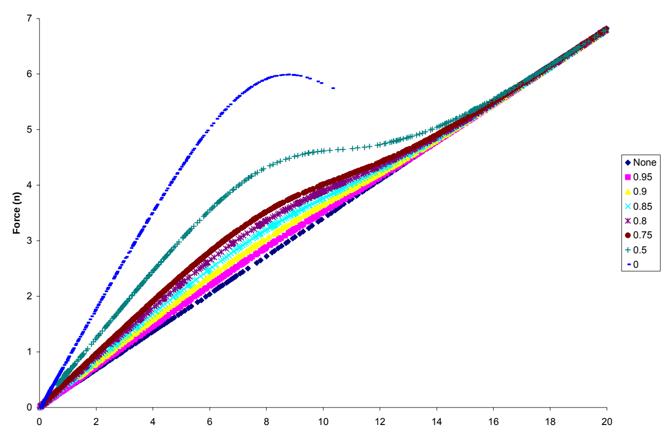

Figure 2. Relation between force and displacement at different difficulty levels. The straight line indicates background stiffness (=1/compliance). Increasing deviations from background make the task progressively easier. The deviations disappear at high displacements produced by application of high forces.

THE TESTING AND PRACTICE SEQUENCE

Volunteer subjects (N = 13) 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 2). 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-test

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). 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. More levels of difficulty, 10, were available in the practice sequence than in the pre- and post-tests. They ranged from 0.972 mm/N to 2.50 mm/N; baseline value = 2.52. 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 3) 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.

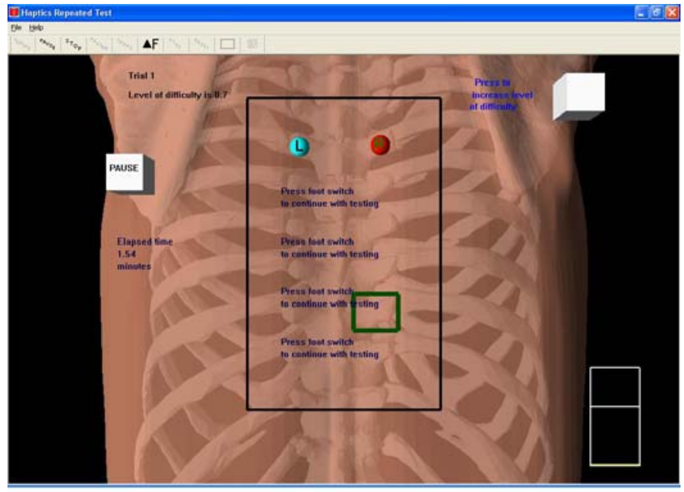

Figure 3. Appearance of the screen following a wrong answer in the practice sessions. The small green box indicates the actual location of the abnormal area. By touching the upper left box with a L or R finger dot, the user can pause the program; by touching the upper right box the user can alter the 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 and Bonferroni's post hoc test. The practice session data was transformed using the arcsine function in order to satisfy the sphericity assumption of the repeated measures ANOVA.

RESULTS

PRE- AND POST-PRACTICE TEST RESULTS

Significant differences in performance levels 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 4). 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. Still 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 no significant pre- to post-practice performance differences were observed.

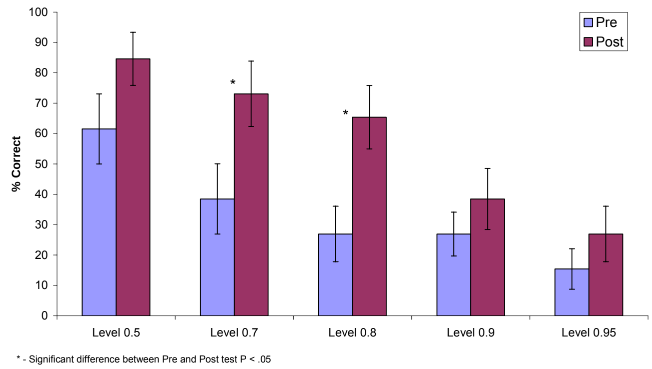

Figure 4. Comparison of percent correct responses in tests before and after the practice sessions as a function of difficulty level of the task. The difficulty levels from easiest to hardest, left to right, correspond to compliance values of 1.51, 1.98, 2.25, 2.35 and 2.45, left to right. Baseline compliance value of normal areas was 2.52.

Performance monitored in the practice sessions revealed gradual improvement over the eight sessions, but only at three of the ten difficulty levels, .70, .75, and .80 (compliance values of 1.98, 2.14 and 2.25). This is illustrated in Figure 5 for the difficulty level of .75.

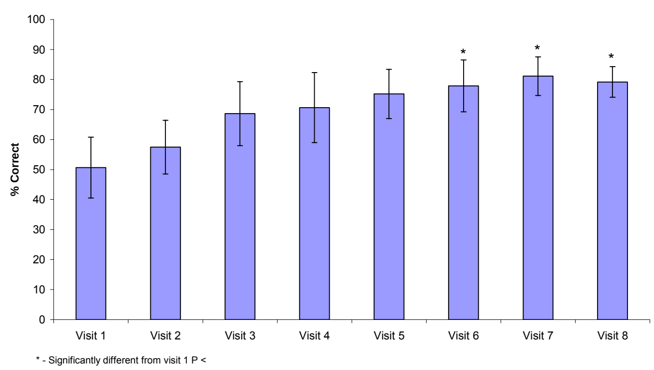

Figure 5. Percent correct localizations as function of practice session (visit) number for difficulty level of 0.75 (compliance value of 2.14). Performance improved over the eight sessions (RMANOVA: $\eta^2 = 0.155$; power = 0.79; P = 0.043). Performance in the last three sessions was significantly (P<0.05) better than performance in the first session.

Results for all difficulty levels and all practice sessions are shown in the 3D plot of Figure 6. It emphases 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 right of the figure, toward level 1, are the easiest tasks, where the compliance is least (making the compliance difference from baseline the greatest). Subjects got nearly 100% of these correct even during the first practice session.

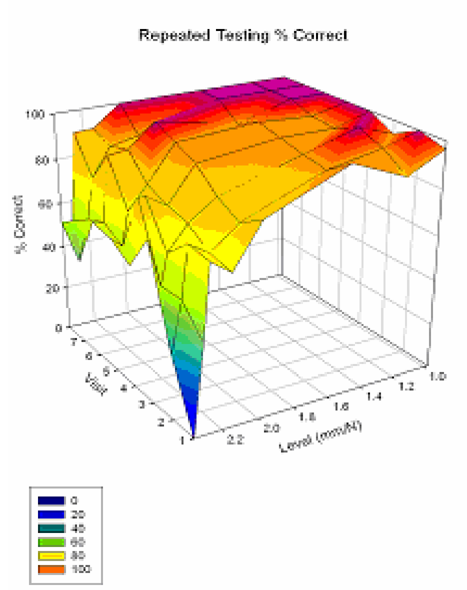

Figure 6. Percent correct localizations during practice as a function of both visit (session) number and difficulty level (designated in units of compliance). As the difficulty level increases, moving from right to left on the graphed surface, performance falls off. At the difficulty levels at which performance falls off, improvement can be seen with increasing visit number.

DISCUSSION

The VHB combines graphics and haptics into the simulation of the human body 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 and thermal 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 that are detectable 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 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

A standard measure in the analysis of sensory systems is that of the limit of detection, the just noticeable difference, JND. 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 set-up was not optimally designed for the precise determination of the Weber fraction, our results do yield an value of 0.11 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 8%, i.e., a Weber fraction of 0.08, 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 the precision of 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, close to that used in the present study, threshold was 25%. De Gersem et al, (2005) referred to an previous study (De Gersem et al, 2003) with a PHANToM yielding a detection threshold of 8-12%. Because no details as to baseline compliance used, or range of compliance values used, were given, we are unable to compare our data with theirs.

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 considerably less than 50%. The fraction of the total test area occupied by the abnormal compliance is only 2.5%, but abnormal areas occur in only a portion of the total area, at a constant distance from the midline of the back. Because there are 12 possible locations of the abnormalities, chance level might be taken as 1/12, or 8%. However, if the subject systematically placed his two palpating fingers on either side of the midline, simultaneously touching left and right regions, he/she would have a 1 in 6 chance (17%) of being correct. Based on this, we estimate the chance level to be no more than 20%. This is consistent with performance at the hardest level in the pre- and post tests (Figure 3). 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 0.40. In the post-test subjects achieved 60% correct at a difficulty level of 0.8. This corresponds to a Weber fraction of 0.11, or 11%. This figure agrees well with the Weber fraction of 8-12% reported by De Gersem et al. (2003).

The improvement in 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%, but performance during the first practice session at that difficulty level was already 70%, similar to the post-test value (Figure 4). The gradual improvement in performance seen at somewhat harder levels of difficulty, 0.75 (Figure 5) 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 force detection.

In the context of clinical palpatory diagnosis training it is not known the extent to which improvement in palpatory skills represents increased ability to feel small differences as opposed to an increased ability to impart meaning to what is felt. Our data now indicate an increasing ability to feel small compliance difference with VHB training, which presumably also occurs with clinical training. Verbal feedback from medical student subjects suggests that experience with the VHB may be also helpful in imparting meaning to what is being felt.

CONCLUSION

The VHB, a haptic simulation of human back, has been used 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 improves performance.

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CONTACT

John N. Howell, Ph.D. is an associate professor of physiology at the Ohio University College of Osteopathic Medicine and Director of the Interdisciplinary Institute for Neuromusculoskeletal Research.

howell@ohio.edu;

http://www.oucom.ohiou.edu/IINR/